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Hot thermal storage in a variable power, renewable energy system

Hinke, Themba D.

Monterey, California: Naval Postgraduate School

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THESIS

HOT THERMAL STORAGE IN A VARIABLE POWER, RENEWABLE ENERGY SYSTEM

by

Themba D. Hinke

June 2014

Thesis Advisor: Anthony J. Gannon
Co-Advisor: Anthony G. Pollman

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HOT THERMAL STORAGE IN A VARIABLE POWER, RENEWABLE ENERGY SYSTEM

Themba D. Hinke
Lieutenant, United States Navy
B.S., United States Naval Academy, 2008

Submitted in partial fulfillment of the
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Author: Themba D. Hinke

Approved by: Anthony J. Gannon
Thesis Advisor

Anthony G. Pollman
Co-Advisor

Knox T. Millsaps
Chair, Department of Mechanical & Aerospace Engineering

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ABSTRACT

This thesis outlines the design of a renewable energy heat generation system with thermal storage for DOD facilities. The DOD is seeking to implement an increased percentage of renewable energy systems at its facilities in order to improve energy security and reduce energy costs. The intermittent nature of renewable energy generation, however, presents a major challenge to full implementation. This shortfall can be overcome by targeted facility-scale energy storage that allows for increased use of renewable-only systems. Since a large percentage of the electric energy used in both residential and commercial facilities is for space and water heating, thermal storage is a viable solution. Presented in this thesis is a method for designing, analyzing, and sizing a facility-scale thermal storage system. The results demonstrate thermal storage is a more cost-effective option when compared to alternatives like battery storage. In addition to being cheaper, thermal storage systems are safer, more reliable, and have a longer life cycle.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	alternating current
CSP	concentrated solar power
DC	direct current
DOD	Department of Defense
ETS	electric thermal storage
GETS	grid interactive thermal storage
kW	kilowatt
kWh	kilowatt-hour
MIT	Massachusetts Institute of Technology
NREL	National Renewable Energy Laboratory
PCM	phase change material
PEV	plug-in electric vehicle
PV	photovoltaic
SCES	super capacitors energy storage
SPIDERS	Smart Power Infrastructure Demonstration for Energy Reliability
TE	thermoelectric
UGE	Urban Green Energy

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I. INTRODUCTION

This thesis presents a system design focused on hot thermal storage to lower DOD energy costs through the practical use of renewable energy. The design is a part of the Naval Postgraduate School (NPS) multi-physics renewable energy system. The NPS facility is a demonstration plant that uses renewable energy to charge a thermal storage system. The project concept is based on a unique hypothesis on energy use, utilizing a variety of storage methods with lower costs than batteries. The goal is to target the end use of energy and to leverage advantages in these alternative methods of storage such as safety and reliability. To this end, it investigates energy storage and generation methods including thermal fluid, chemical and solid state.

The goal of the demonstration plant is to serve as a model for Department of Defense (DOD) facilities for decreasing costs and improving energy security by implementing thermal storage paired with a novel power matching control strategy. In the future it may serve as a potential model for forward operating bases or facilities in remote locations where dependence on fuel transported to the facility poses a significant risk [1]. Capable of running in either an on-grid or off-grid configuration, the demonstration plant design aims to improve facility energy security at a lower installation cost to other storage methods and provides an alternative method for reducing the size of facility backup systems.

The intermittent nature of renewable generation presents a major challenge to full implementation of renewable only facilities. This design thesis targets energy storage, specifically the thermal storage of heat. Chapter II evaluates the effects the addition of thermal storage has in overcoming the intermittency shortfall. It compares thermal storage to conventional battery storage options and demonstrates it as a more cost effective option that is arguably safer, more reliable, and longer lasing. Chapter III presents commercially proven and available energy collection, conversion, and storage systems and equipment. Chapter IV presents a method for innovative integration of the technology into a scalable, facility suitable heat storage system.

A. MOTIVATION

The goals of the DOD, as laid out in the DOD Energy Policy [2] are improved energy performance for installations and expanded use of diversified renewable energy systems. The policy is for facilities to, where cost effective, increase the utilization of distributed electric power generation through wind, solar, geothermal, and biomass renewable systems [3]. In addition to this, through the DOD Smart Power Infrastructure Demonstration for Energy Reliability (SPIDERS) [4], [5] program, several initiatives are in place to integrate improved microgrid infrastructure into the DOD profile. These efforts focus mainly on power generation and infrastructure.

Renewables capitalize on natural sources that are not always dependable. The sun shines with the same irradiance every day and changes can be predicted based on the latitude, time of year, and time of day. The cloud cover in an area, however, cannot be predicted beyond a few hours or at most a few days in advance. Wind predictions are even more challenging. A practical solution to achieving greater usage of these renewable sources and overcoming the challenge of intermittency is energy storage. For this to be possible, large capacity systems that are inexpensive, safe, and enduring are required.

B. OBJECTIVES

The objective of this thesis is to present an analysis of alternatives for some of the different ways to accomplish hot thermal storage and the considerations weighted heaviest by the project team at NPS, including: system sizing and component selection. Specific objectives are:

- Compare and contrast battery storage to thermal storage.
- Simulate various storage systems and determine the effectiveness of storage in overcoming intermittency.
- Review the methods and equipment for renewable energy collection and thermal storage.
- Present a facility scale design based on renewable energy collection and thermal storage.

C. METHOD

Energy consumption, specifically end uses of electricity, offers potential for exploration of a targeted storage solution. Thermal loads for residential use constitute a significant portion of the electrical energy consumed, as can be seen in Figure 1. Space and water heating, constituting 15% of electrical energy consumption in homes, is an area where targeted multi-physics storage solutions could be applied to reduce costs [6]. Multi-physics storage is a thermal fluid, chemical or solid state system that stores energy. From large-scale systems using molten salt to residential scale units using water or thermal bricks, hot thermal systems are a commercially viable means to achieving thermal storage for end use in space and water heating.

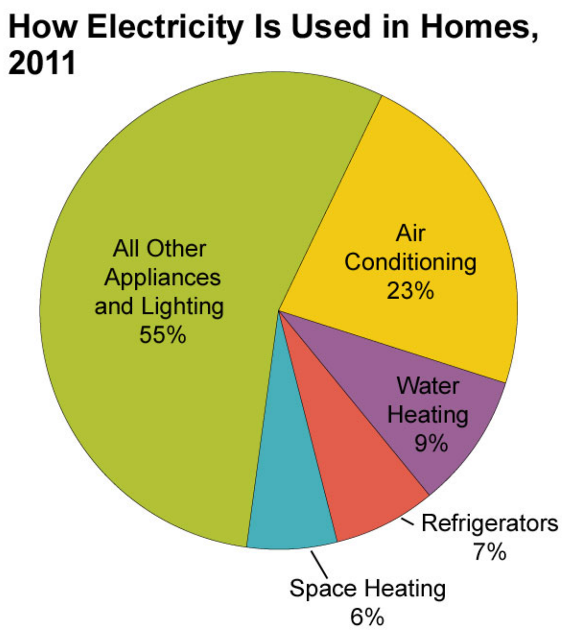

Figure 1. Electrical energy by end use for U.S. homes, from [6].

When compared to battery storage, thermal storage is arguably equivalent in energy density but superior in cost, safety, and life cycle. On the gravimetric energy density versus volumetric energy density chart for batteries, thermal storage is in the region between lead acid batteries and nickel-zinc batteries, demonstrating equivalence to these chemical storage methods. This is depicted in Figure 2.

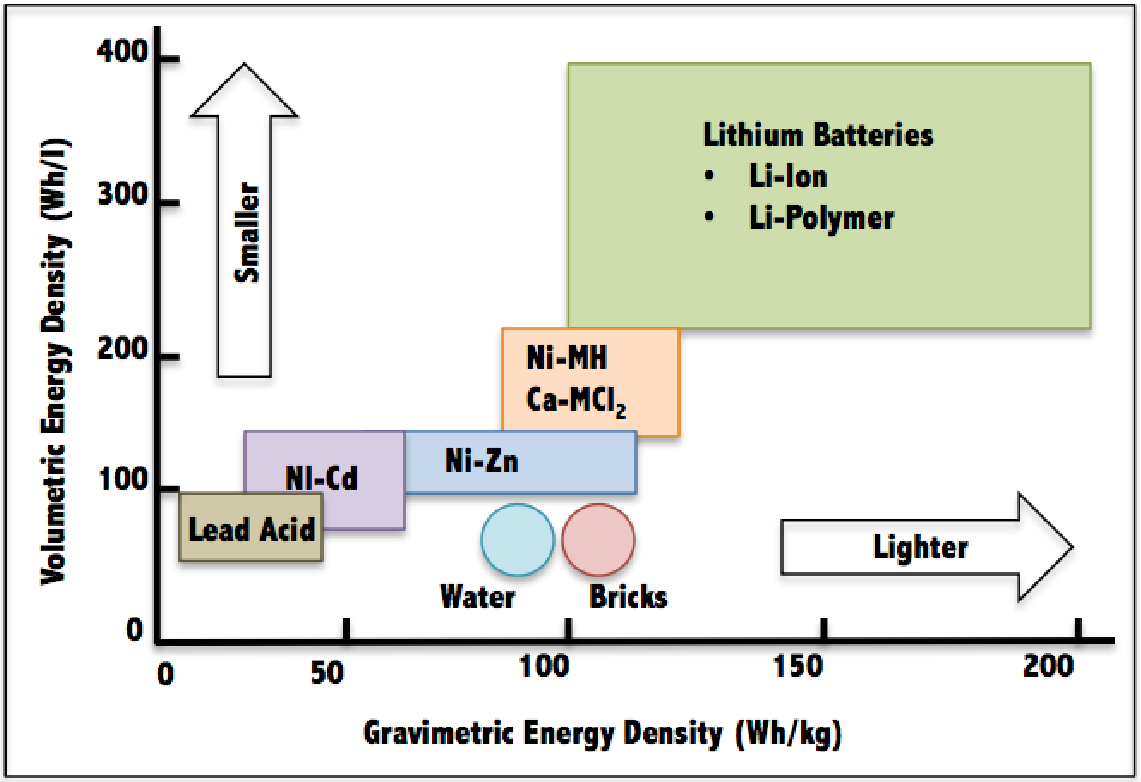

Figure 2. Gravimetric vs. volumetric energy density comparison of battery technology to hot thermal storage methods, after [7].

In a comparison of the installation cost per kilowatt hour (kWh) of hot thermal storage to battery storage, thermal storage in bricks is 20% cheaper and in water is 76% cheaper than the least expensive battery technology, lead acid batteries [8]. In addition to being impervious to deep cycle discharge damage, thermal storage systems have a nearly infinite life cycle. These comparisons can be seen in Table 1.

Storage Method	Hot water	Thermal brick	Lead-acid battery	Lithium-ion battery
Purchase Price per kWh	\$20	\$110	\$150	\$400
Cycle Life (cycles)	10+yrs	10+yrs	300	1000

Table 1. Tabular comparison of batteries to thermal storage, after [8].

The basis for these comparisons is detailed further in Chapter III. Both methods of thermal storage are presented as a cost effective solution. There are neither chemicals nor acids used in thermal storage, nor is there a chance of thermal runaway, making these methods safer than battery storage. With advantages in longevity, safety, and cost, thermal storage systems represent the best value for facility energy storage.

Improved storage is a possible solution to solving the intermittency challenge of renewable energy systems. The thesis presents options for hot thermal storage in Chapter III. The design of a facility-suitable system that couples renewable energy generation with heating load-focused storage is presented in Chapter IV. Taken together, this design hopes to increase the utilization of renewable energy. In DOD facilities, this will increase energy security and may reduce costs. The design allows for diversified generation through an increased presence of solar thermal collectors, solar photovoltaic collectors and small wind turbines coupled with facility suitable thermal storage systems.

D. LITERATURE REVIEW

The body of knowledge in distributed generation, microgrid implementation, and thermal storage continues to grow. The worldwide climate change discussion, and energy policies like those of the DOD, have advanced research into the field even more. Strictly looking at DOD facilities, there have been several methods to date that attempted to address microgrids and energy storage as a way of improving utilization of renewable energy sources.

An MIT microgrid study on energy security for DOD installations [9] detailed projects on microgrids and provided a comprehensive look at large scale use of renewable energy generation across the DOD. The typical method for achieving energy security in domestic, grid tied DOD facilities is to have single backup diesel or gas turbine power generation system for each mission critical load. This has resulted in many backup generators on a single base. The fuel reserve is scaled based on the mission importance or the duration of anticipated intermittent outages. The addition of renewable systems to DOD facilities has been done in the same fashion as the larger commercial

market. Systems are installed and fed onto the commercial grid. When the grid is unavailable, these renewable systems are taken offline by an anti-islanding safety mechanism. Even with an increased presence of renewable systems, there is limited ability of the facilities to island, disconnect from the grid, and meet all of its power requirements from its own sources. Several efforts are in progress to design improved microgrids so these facilities can achieve energy security for the entire base instead of only a few critical missions. For installations with an operating microgrid, the bulk of the power generation comes from conventional diesel generators. The integration of relatively high concentrations of solar photovoltaic (PV) has been attempted using advanced control strategies to optimize usage and plug-in vehicles, lead acid batteries and sodium metal halide batteries for storage. The MIT study emphasized the increased integration of renewable sources will require a high degree of sophistication, including advanced control and energy storage systems.

In looking at one of these storage methods, Ersal et al. [10] discussed the impact of controlled plug-in electric vehicles (PEV) on microgrids and its specific application to the SPIDERS project at Camp Smith, HI. Using the charge and discharge capability of PEV batteries and incorporating control algorithms, energy storage and regulation on the microgrid were modeled. They concluded, based on the chosen control architecture, that PEVs could be used as a facility battery, regulating voltages and frequencies in the microgrid. This was demonstrated in practice at Wheeler Army Airfield, HI, by Skowronska-Kurec et al. [11] who noted the challenges of coordinating the bidirectional energy flow in the vehicles with the operational usage of the vehicles. The use of PEV as batteries resulted in reduced vehicle range.

In the area of thermal storage, research and commercial operation covered a broad range of applications. This thesis was follow-on to Olsen’s work [12], which provided a theoretical framework for the integration of cooling into a micro grid combined with thermal storage. Olsen detailed the concept of the integration of wind power with a chilling unit and ice storage. She investigated the feasibility of a variable speed chiller following the wind to increase the energy usage. When wind was available, the chiller

would freeze a cold storage water tank for future cooling use. Along these same lines, Davis [13] also involved the integration of renewable energy with cooling. The experimental work used a commercial ice maker directly coupled to a wind turbine to preserve fish in developing nations. Her work proved not only that thermal storage of renewable energy could be accomplished, but also some commercial chilling equipment could be run to match the variable current and voltage of wind energy. These theses were specific to ice storage; but, in the larger academic community, thermal storage and its integration with renewable energy has been widely explored.

Kazmerczak et al. [14] published the results of experimental work in a thermoelectric-based hydronic cooling and heating device. A thermoelectric (TE) module is a small solid state device that can operate as a heat pump. They succeeded in a small-scale experimental TE module setup that accomplished sensible charging of small hot water and cold water tanks. They also theorized on powering the system directly using solar energy and on a larger scale.

On a grid scale, hot thermal storage has been attempted through Grid-Interactive Electric Thermal Storage (GETS) water heating [15], [16]. The Steffes Corporation has been using this concept in concert with utility companies to improve the integration of renewable energy into the commercial grid. Under this scheme, residential water heaters in a given area are temperature controlled at the utility company. When renewably generated energy is available but grid usage is low, the utility company raises the thermostat temperature of residential water heaters. This change in temperature allows for increased energy usage in off peak times. It is transparent to the residential customers since mixing before use cools water that is too hot coming from the water tank. The utility company can also reduce the temperature of the residential water tanks during periods of peak grid usage. In effect, the program capitalizes on the periods of peak renewable energy availability and stores that energy thermally in the residential water heaters.

Beyond water, work has occurred for several other storage mediums. Pokhrel et al. [17] published the results of experimental work on paraffin and graphite phase change material (PCM) for use in thermal storage. This and other types of thermal mass systems are a potential method for reducing the size of thermal storage systems with the drawback of a very specific temperature range for optimal operation.

Ma et al. [18] presented a potential renewable electricity generation solution that uses thermal storage in the form of molten salt. On a grid scale, off-peak electricity, converted by ohmic heating, and thermal energy from a concentrated solar power (CSP) plant, would be stored and a Rankine cycle steam plant would be used to extract the latent heat of the molten salt. This would allow peak wind and solar energy to be stored and dispatched later to produce high-value, peak-demand electricity.

More in concert with microgrid efforts, Wei et al. [19] discussed the application of super capacitors for energy storage (SCES) in a microgrid. They concluded the addition of SCES to a microgrid could improve the power quality of a renewable source system for use in important load equipment because it could very rapidly respond to changes in the incoming power. Because of the high cycle life and ability to absorb the high power density and energy density characteristics of renewable sources, a super capacitor was presented as an ideal buffer for a microgrid over a battery.

Integrating this wide variety of microgrid and multi-physics storage options is complex and many methods have been explored [20], [21], [22], [23]. Renewable energy sources suffer intermittency challenges. Whereas solar has its energy generation period during the day, wind power typically blows the most in the mornings and the evenings. To complicate matters more, these renewable resources are not distributed evenly across the globe or even the United States, as evidenced by Figure 3 and Figure 4.

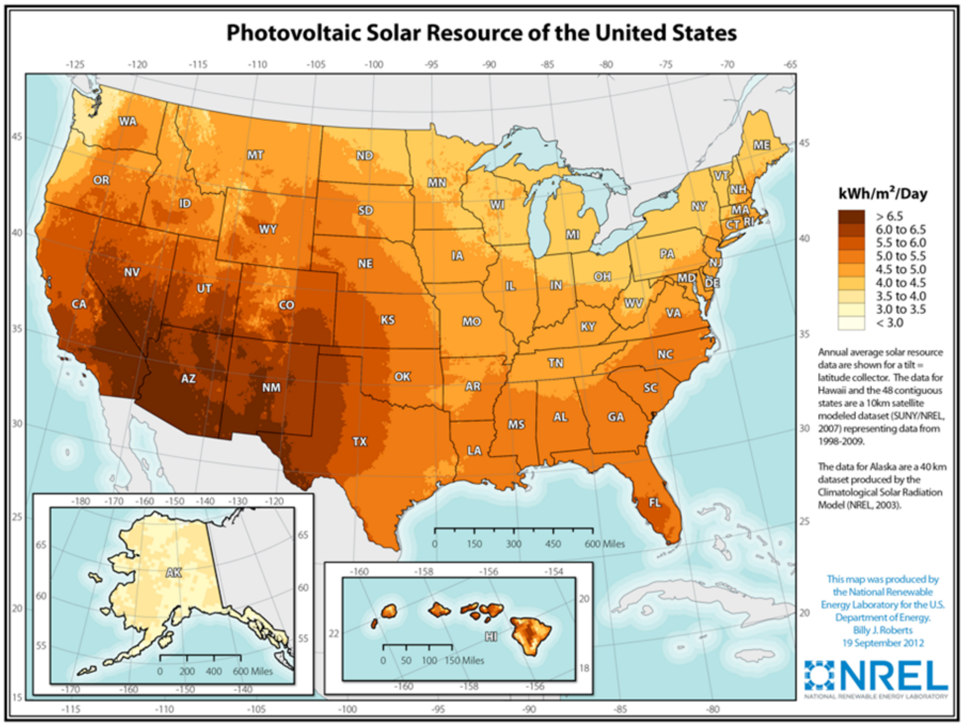

Figure 3. Photovoltaic solar resources of the United States, from [24].

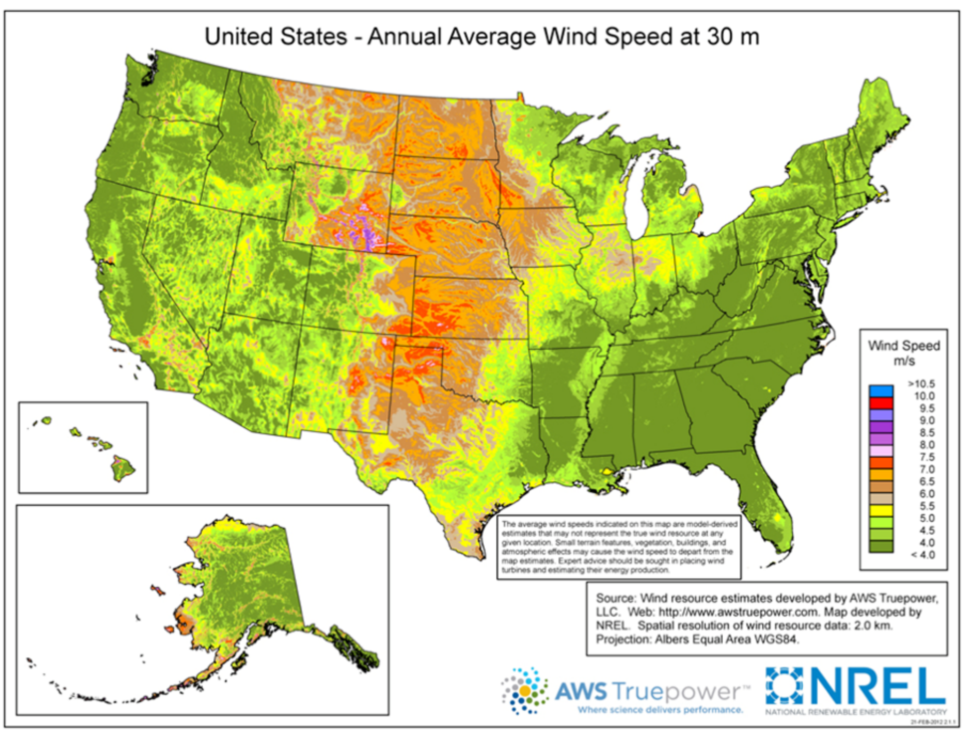

Figure 4. Annual average wind speed at 30m in the United States, from [25].

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II. OVERCOMING INTERMITTENCY WITH STORAGE

This chapter presents a method for analyzing the effectiveness of storage in overcoming the intermittency challenges of wind power. Using wind data from Monterey, California, and keeping the available installed wind turbine capacity constant, a sample demand curve is scaled to compare the effect of various storage system sizes. The associated MATLAB code, as well as an explanation of its implementation (for all figures and calculations contained in this chapter), is presented in Appendix A. This chapter presents a limited set of results. Complete results of the parametric analysis are presented in Appendix B.

A. ENERGY SUPPLY AND DEMAND

Olsen [12] demonstrated a method of analysis to determine accumulated energy based on the wind data at the Monterey Regional Airport and a 4 kW Urban Green Energy (UGE) wind turbine. Applying this method for a ten-year period from 2000–2010, a graph of the power generated versus time was generated and is presented in Figure 5. This energy, accumulated with a Simpson's Rule integration over the time period, is presented in Figure 6. This available installed wind capacity was kept as a constant for this study.

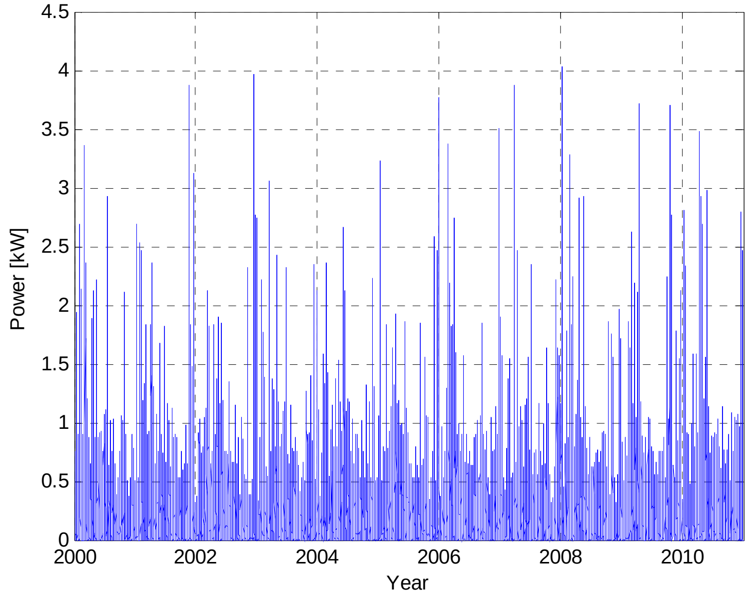

Figure 5. Power from 4 kW wind turbine in Monterey conditions vs. time, after [12].

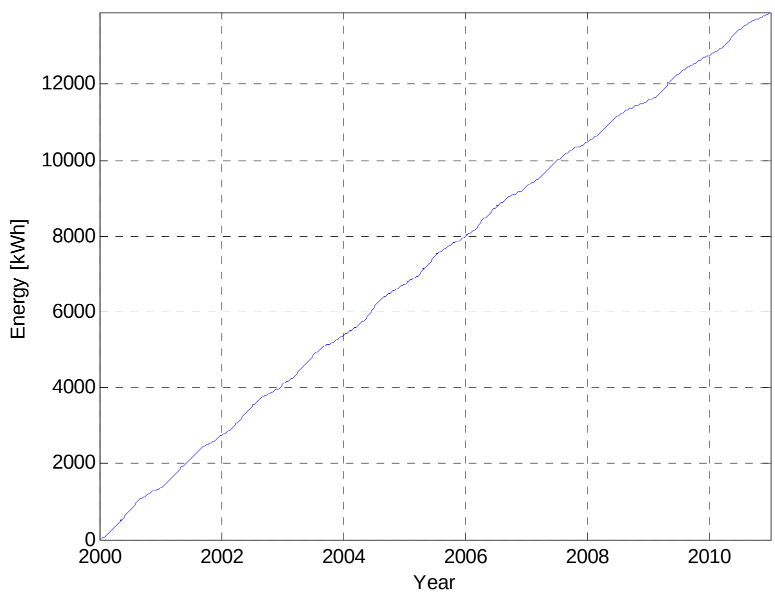

Figure 6. Total energy accumulated over the 10-year period, after [12].

Heat usage in a specific facility can be measured with instruments measuring gas and electric usage, and losses can be predicted using software available from the Office of Energy Efficiency and Renewable Energy [26]. For this analysis, a daily demand curve, based on a metered fractional load profile for residential energy use, was used [27]. This demand curve is shown in Figure 7. Energy demand was accumulated through the day in the same way as the energy supply but was represented with a negative slope to indicate demand, as shown in Figure 8.

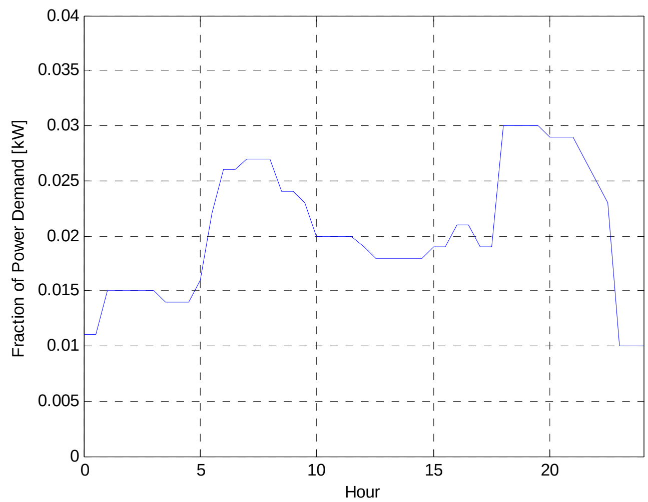

Figure 7. Sample power demand curve for a day, after [27], [28].

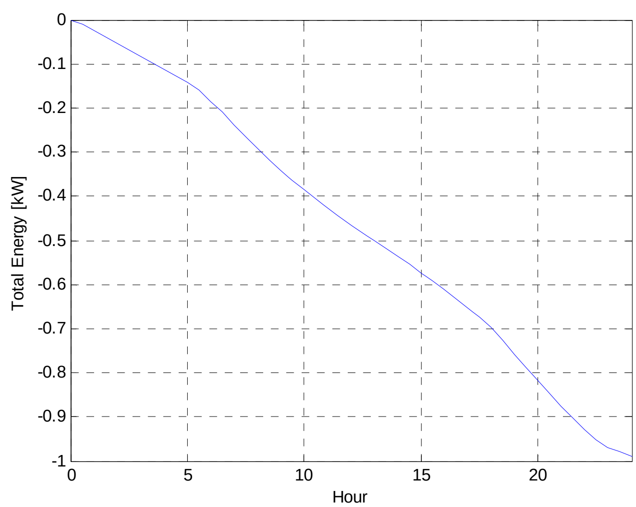

Figure 8. Sample demand integrated over the day.

This demand curve could then be scaled to produce an energy use profile that was larger, smaller, or equal to the energy supply profile. The 10-year period of energy demand equal to the wind energy supply can be seen in Figure 9.

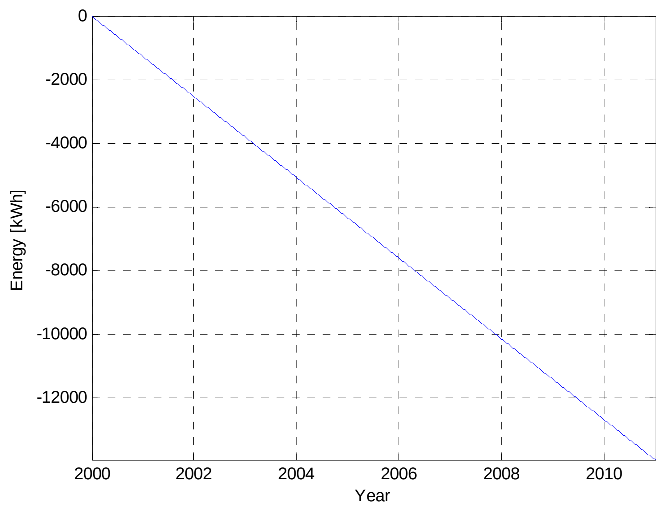

Figure 9. Total energy demand accumulated over the 10-year period.

Closer analysis of this clearly equivalent macroscopic representation of supply and demand shows the reality of the challenging intermittent nature of renewable energy, in this case, wind energy. From this same data, a seven-day period of supply and demand is shown in Figure 10. This figure shows many intervals where supply falls significantly short of demand and vice versa. The same seven-day period is shown again as accumulated energy in Figure 11. From this figure it is evident that supply met demand over time. The figures demonstrate that while supply may meet demand, a renewable only system is intermittent (which for most facilities, is an unacceptable situation.) A method for balancing supply with demand, in order to minimize intermittency is required.

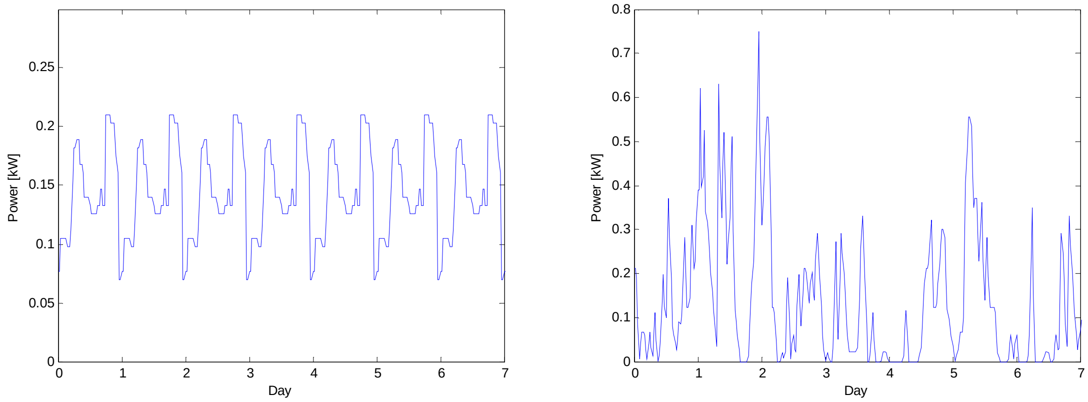

Figure 10. (left) Sample demand and (right) a representative sample of wind data over a seven-day period.

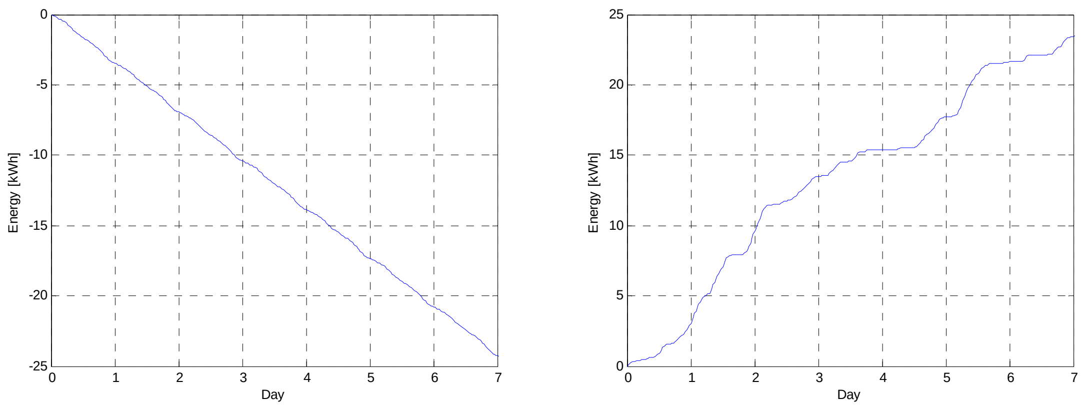

Figure 11. (left) Accumulated supply and (right) accumulated demand over a seven-day period.

B. ENERGY STORAGE AND SYSTEM SIZING

With the supply and demand determined, the next step was the addition of a storage system to balance the time periods when the two did not match. Thermal storage systems are not unlimited in size and can only absorb energy to a finite point. The storage system energy is initially set to zero, as would be expected in a thermal storage system, and changes based on the prevailing environment condition until the upper limit is reached at which point it must be dumped via a dispersive load or sold to the commercial grid. In the same way, the zero condition would require purchased energy to meet

demand. In the model, the zero condition and the maximum condition were plotted as flat lines. The method for calculating storage was to begin at zero storage, add the power generated by the wind over a half hour increment and then subtract the demand for the same period.

A demonstration of the method for plotting the storage is shown for the same seven-day period in Figure 12. The plot contains four significant features. The first is that the storage is bound by upper and lower limits. The second is the status of charge for the storage system as indicated by the blue line. During periods of high wind and low demand, the storage system accumulates energy. When the maximum storage capacity is reached, the power is available to be sold to the commercial grid. Surplus power, the third significant feature, is indicated by the green line. During periods of low wind and high demand, the storage system draws down, and when it reaches zero energy, power will need to be purchased or supplemented from alternative sources. This fourth significant feature is indicated by the red line.

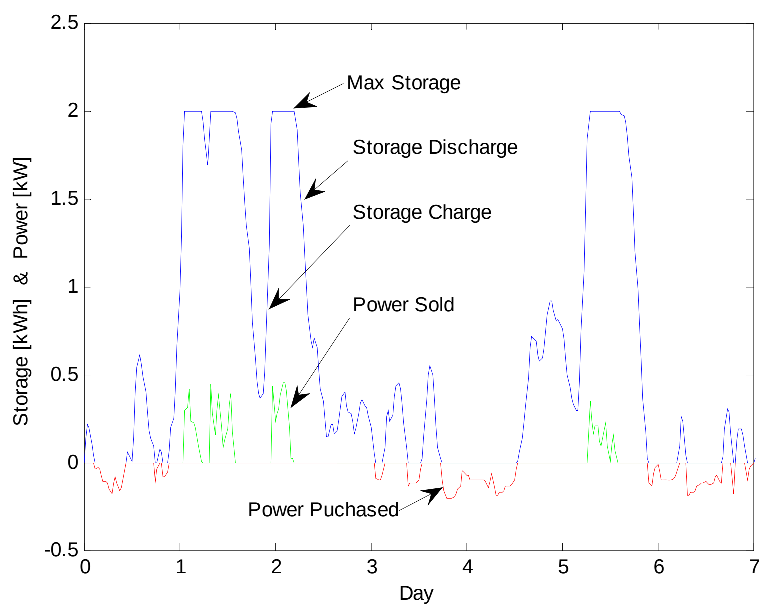

Figure 12. Seven-day simulation of the energy storage level.

Modeling past energy collection data and anticipated thermal loads provides a method for analyzing the size of the thermal storage systems. Using the 10 years of wind

data and projecting the sample demand curve scaled to match supply over the same period, different thermal storage systems were compared. Using the same color indicators as those above, the various parameters can be plotted. A 13.5 kWh size storage system, like the one purchased for the NPS facility, can be seen in Figure 13. Increasing the maximum limit of the storage system allows the system a larger dynamic range to account for the seasonally available supply. A 150 kWh storage system is presented in Figure 14. While only a few size options are presented here, many options exist for sizing a system. An ideal storage system should be sized so once an initial charge of the system has been established; neither the top or bottom limit is reached. This would mean the maximum amount of renewable energy was being absorbed into the thermal storage system and all heat loads are being met without the need for a supplemental energy source.

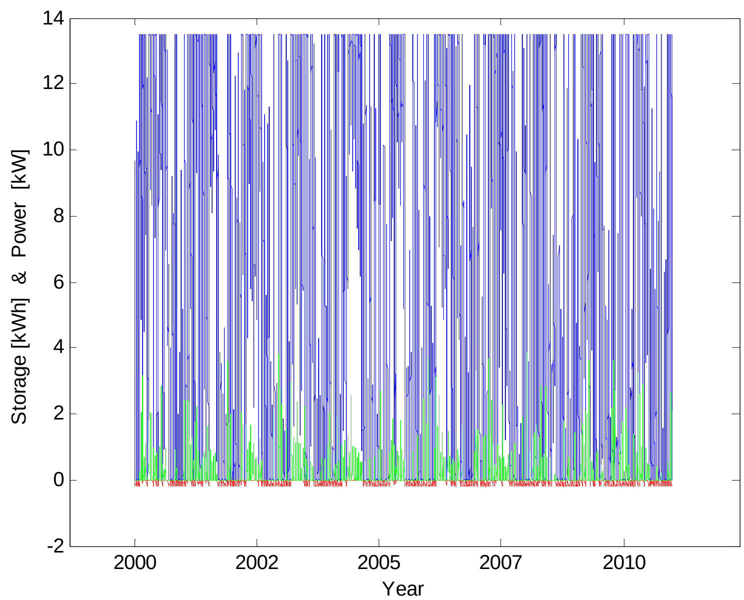

Figure 13. Energy storage level for a 13.5 kWh system over the 10-year period.

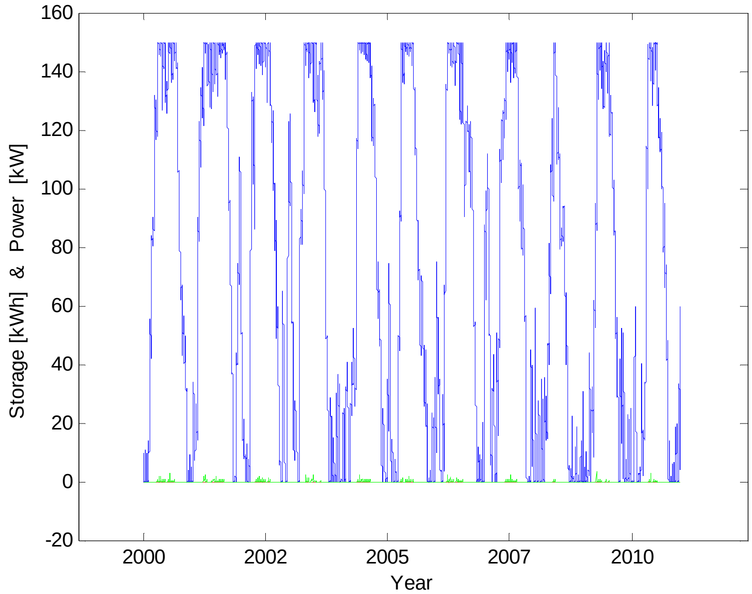

Figure 14. Energy storage level for a 150 kWh storage over the 10-year period.

The order of magnitude size difference between the first and last sample storage sizes showed the need for optimization of the system and a more thorough method of analysis. In this next study, 4 capacity options, 13.5 kWh, 50 kWh, 100 kWh, and 150 kWh systems were compared again with a demand profile that exceeded supply by 25%, as well as a profile that fell 25% below supply. A few additional demonstrable results are shown from the three demand curve studies in Figure 15 and Figure 16. When demand does not meet supply, the storage systems cycle regularly but when supply exceeds demand, a clear overcapacity is evident. With an excess of energy supply, the storage system remains near a full charge; and, with a shortage energy supply, the storage system is fully discharged an increasing amount of the time.

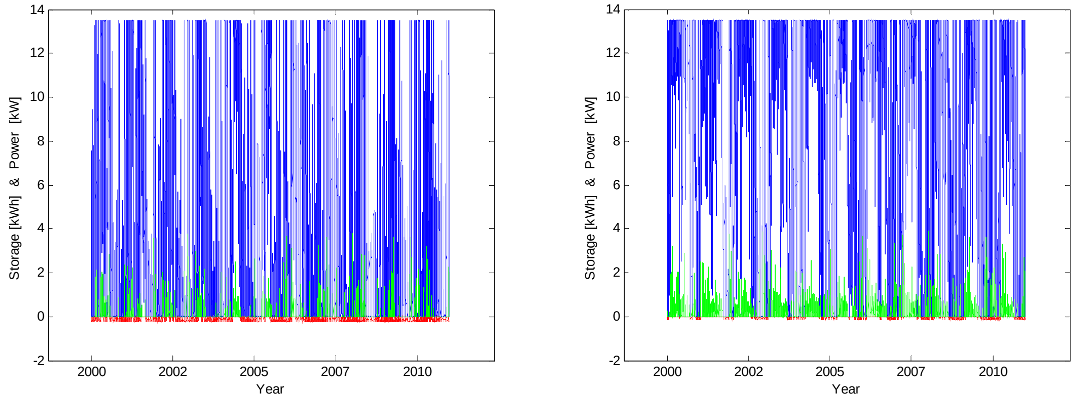

Figure 15. (left) Storage results for a 13.5 kWh system where demand exceeded supply and (right) a 13.5 kWh system where supply exceeded demand.

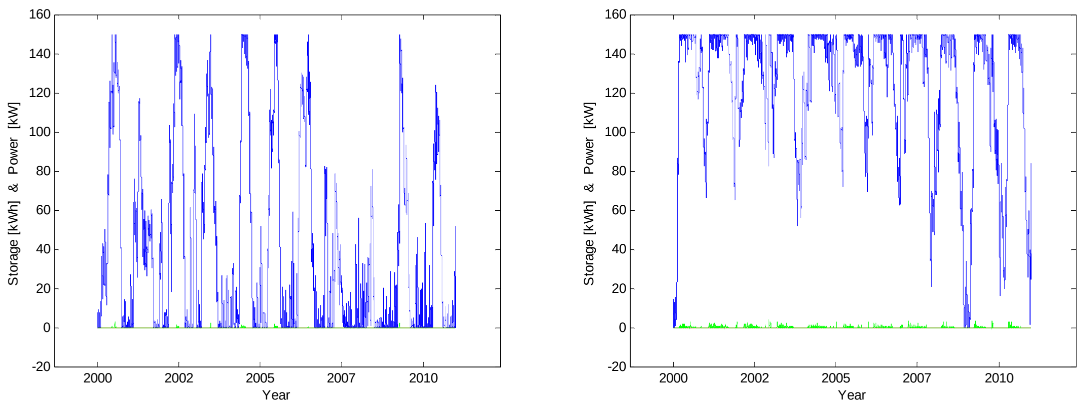

Figure 16. (left) Storage results for a 150 kWh system where demand exceeded supply and (right) a 150 kWh system where supply exceeded demand.

The results for all demand profiles and sizes were collected numerically, and the systems compared based on: 1) the percentage of time the spent at the upper and lower bounds of the storage level, 2) the percentage of energy demand that was not met over the 10-year period, and 3) the percentage of surplus energy generated and available for sale. This numerical analysis was repeated for a demand profile that exceeded supply by 25%, as well as a profile that fell 25% below supply. The results of this are shown in Table 2. The same results are also shown in bar graph form in Figure 17. Note: these results are for boundary cases. There was a 70% reduction in the purchased energy for the case of the smallest storage capacity and a demand curve 25% larger that the supply generated.

There was a 99.6% reduction in the purchased energy for the case with a large capacity storage system and a demand curve 25% smaller than the supply generated. These two boundary case results are highlighted in green in Table 2.

	Storage Size	13.5 kWh	50 kWh	100 kWh	150 kWh
Demand=5.3kW 25% Smaller than Supply	Upper Limit	14.8%	13.1%	12.5%	12.3%
	Sold	32.9%	28.4%	26.4%	25.8%
	Lower Limit	11.2%	4.2%	1.3%	0.5%
	Purchased	9.5%	3.6%	1.2%	0.4%
Demand=7kW Equal to Supply	Upper Limit	8.0%	6.1%	5.2%	4.3%
	Sold	20.2%	14.1%	11.1%	8.9%
	Lower Limit	23.6%	16.6%	13.6%	10.6%
	Purchased	20.0%	14.1%	11.2%	9.0%
Demand=8.8 25% Larger than Supply	Upper Limit	4.0%	1.9%	1.2%	0.6%
	Sold	12.3%	5.4%	2.8%	1.3%
	Lower Limit	35.7%	29.2%	26.9%	25.5%
	Purchased	30.2%	24.8%	22.8%	21.6%

Table 2. Tabular results of the parametric analysis of the various storage options with highlighted boundary cases.

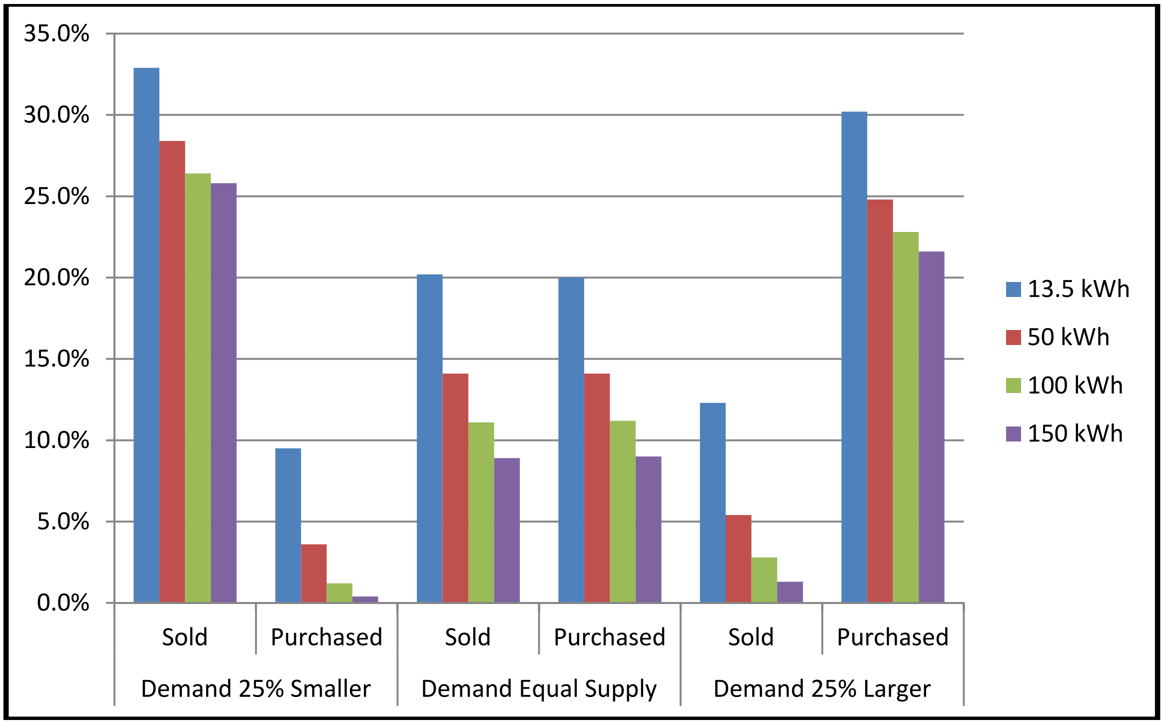

Figure 17. Bar graph of the various storage methods and sizes vs. the percentage of total energy.

C. BACKUP SYSTEMS

The decision on how to size the system has a significant effect on its use as a backup in the event of grid failure. As stated in Chapter I, the NPS Multi-Physics Renewable System has an objective of creating a system capable of on-grid and off-grid operation with the hope of increasing energy security. In a facility, the backup power systems need to be sized to account for the entire energy end use spectrum. Thermal storage can reduce this electric backup requirement by supplementing the thermal load. In addition to this, equipment used in space heating and cooling often creates large transient start-up loads. If the system no longer needs to account for a significant transient load, it does not require as much over capacity. Another example of the effect of thermal storage was demonstrated in the sample demand used for this analysis. To build a system capable of producing sufficient hot water and space heating, at peak times, required an extreme over capacity in the off-peak times. On an industrial scale, space heating and water heating loads typically occur during hours of operation and again, the

backup system would need to be designed for this period of peak usage. These short duration times, with large power loads, become the sizing factor for the system instead to meet the overall energy requirements. By storing thermal energy to meet those high power load periods in the form in which it is to be used, transient loads are removed from the size requirements of the system. Electric power backup systems can now be sized only to account for the smaller, more consistent loads.

III. TYPES OF SYSTEMS

Many options exist for implementation in an energy system design. This thesis will not review all types of systems; rather, it presents several suitable off-the-shelf components for a facility scale renewable generation system with heat storage. It reviews the available energy sources as well as methods for energy conversion and storage.

A. ENERGY RESOURCES

Two types of renewable energy capture are presented in this chapter: direct heat energy and electric energy. These types of energy come from a wide variety of source and the practicality of each is highly dependent on the local environment, as each one has location specific characteristics and may not necessarily be available in all cases. Types of direct heat energy systems include solar thermal, waste heat, and geothermal systems. Types of electric energy systems are wind electric and solar photovoltaic systems. Careful consideration should be made of the physical and geographical location to maximize the energy collected. Samples of these types of resources were the figures from the National Renewable Energy Laboratory (NREL) [29], presented in Chapter I, showing the solar irradiance and wind speeds of the United States. In addition, the strengths and weaknesses of individual systems should be considered. For example, system based on solar thermal may not be the best solution in locations where the shortest days are the coldest time of the year. Likewise, in locations where there is a large temperature differential between the day and night, such as the desert, both heating and cooling are required in a single day.

B. DIRECT THERMAL ENERGY

Using thermal energy directly would be any type of system capable of harvesting or generating heat with no energy conversion required. These types of system can be passive or active, relying only on natural thermal gradients for moving heat or depending on a pump to move heat from one area to another. This thesis is limited to waste heat and solar thermal heat.

1. Waste Heat

In a location where both heating and cooling are required, the chiller is a potential source of waste heat. An air cooler chiller rejects air at an elevated temperature from the ambient. Heat can be harvested from this elevated temperature air with a crossflow liquid-air heat exchanger. The warm air coming off the chiller passes over a second heat exchanger and to the water. Relative to a liquid-air heat exchanger, a more efficient heat exchanger would be a liquid-liquid heat exchanger. Using this elevated temperature liquid for thermal energy storage increases the complexity of the chiller. With a variable speed chiller, careful consideration needs to be made for the volumetric flow rate and temperature of the cooling water. The partially warmed water in the storage system needs a high thermal load application since recirculation of the warmer water quickly degrades the performance of the chiller. A model of a cold thermal storage system with a chiller that could be used for waste heat recovery is presented in Figure 18.

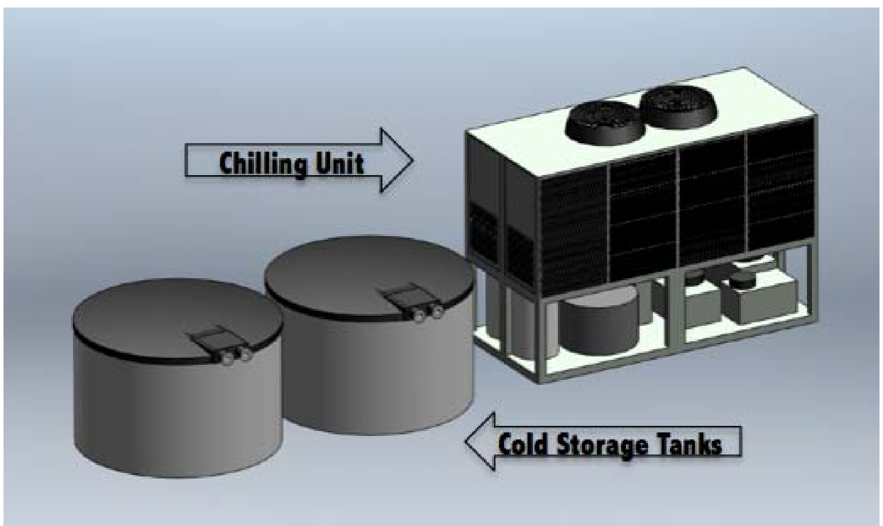

Figure 18. Model of a cold thermal storage system

2. Solar Thermal

Solar thermal is another source of direct heat generation for thermal storage. Heated water (or a water-glycol solution), from the arrays, can either be pumped directly

into the hot water tanks or, in the case of a water-glycol solution, passed through an indirect heating coil inside the water tank. Solar thermal systems have a greater maintenance footprint than solar photovoltaic due to piping and pumps associated with moving the heated fluid. From a utility standpoint, the use of solar thermal versus photovoltaic is debatable—with maintenance, ease of use, and the danger of freezing in cold climates being key factors for consideration. For making heat, solar thermal cells are more efficient, capturing the largest spectrum of the sun's radiated energy whereas photovoltaic cells are limited to specific bandwidths. A system setup can be as simple as a hot water storage tank and a solar thermal collector, as depicted in Figure 19.

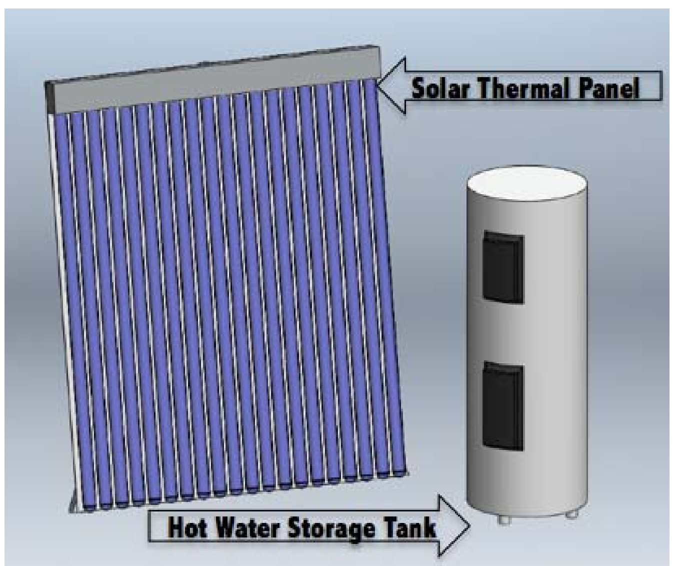

Figure 19. Model of a solar thermal array and a hot water storage tank

C. ELECTRIC ENERGY

Electric heating is a conversion of electric energy to heat energy. It has two significant advantages over direct thermal heating: it is easily controllable and it is capable of reaching much higher temperatures.

1. Wind and Solar Electric

There are two sources of electric energy investigated in this thesis; wind electric and solar PV. Solid models of the vertical axis turbine and solar PV array used in the current study are presented in Figure 20. Wind turbines generate power in the form of so called “wild AC” meaning variable frequency and voltage AC power. PV energy generation is variable DC voltage.

Unlike solar thermal and waste heat, electricity allows for storage in more ways than hot water. Resistive heating is a simple option with a one-to-one conversion of the electricity into heat and has the advantage of creating very high temperature thermal storage. In addition to resistive heating, the electricity can be used to drive a heat pump. While a heat pump is the more efficient of the two options, it is limited by the fact that it operates with a gas cycle and a compressor (so stable power is required). Its coefficient of performance is dependent on ambient temperature.

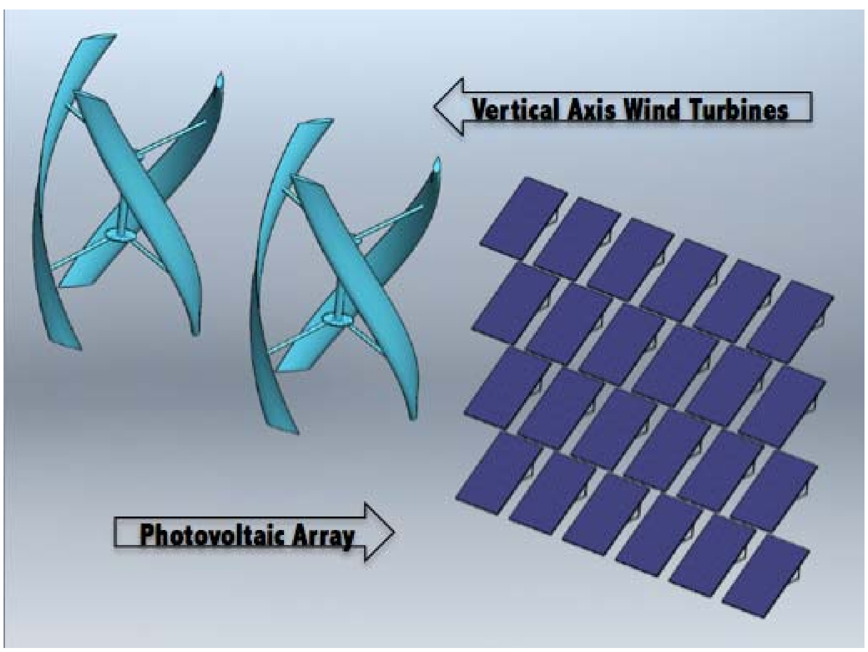

Figure 20. Model of a vertical axis wind turbines and an array of solar PV cells for electricity generation

D. MICROGRIDS

Solar electric and wind electric renewable energy can each be used independently, but combining the two into a single system does require a power stabilizing mechanism. As was presented in the literature review, a microgrid is arguably the best method of power stabilization and management. A battery or potentially a supercapacitor coupled with AC to DC inverters stabilizes the power. Viable solutions are available for either an AC or DC microgrid as well the option to tie that microgrid to the commercial grid. For an AC grid, options exist for both single phase power systems as well as three phase power systems. Energy management is important in a microgrid since there are wide swings in renewable energy generation. Microgrids are designed with energy dispersion systems in either a resistor bank rejecting heat to the ambient air or to a water tank. A grid connected microgrid allows for islanding, continuing to provide power while disconnected from the grid. In effect, it becomes an off-grid power system. Conversely, purely grid-tied renewable generation is shut off by anti-islanding safety features when grid power is removed. Stable power allows for a wide array of heating and thermal storage solutions. A model of the three phase microgrid installed at the NPS Turbopropulsion Lab is presented in Figure 21.

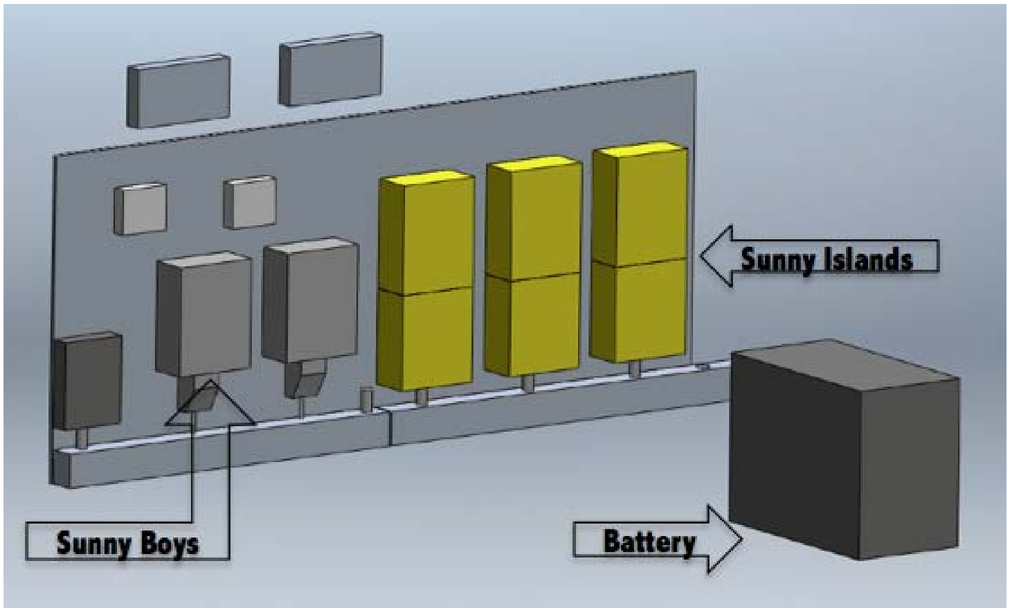

Figure 21. Model of the NPS 3-phase microgrid

E. STORAGE OPTIONS

Two forms of thermal storage, thermal fluid and thermal bricks, are facility-scale appropriate. As noted in the Chapter I, these are also relatively inexpensive compared to battery storage. Direct thermal energy collection requires some form of fluid storage system like the hot water tank presented in Figure 19. Water is the most universally available and least expensive working fluid, but is limited in its energy storage capacity in some cases. To avoid increasing significantly the complexity of a water-based energy storage system, temperature must be limited to its boiling point. Unpressurized thermal storage tanks using water are limited to 82^{o}C (180^{o}F) for safety concerns. Other fluids such as thermal oils are capable of much higher temperatures; although, as stated, this increases the complexity of the storage system. Thermal bricks, typically made of a high density iron oxide compound, have a maximum temperature of 760^{o}C (1400^{o}F) [30]. Heated with a resistive element, these bricks can transfer energy to either an air exchange room heating system or to water in a hydronic system.

1. Bricks

The specific technology chosen for initial integration into the NPS facility was a Steffes Electric Thermal Storage (ETS) Room Unit (presented in Figure 22). The small space heater has a 13.5kWh storage capacity and is powered by single phase 110V AC power [31]. This unit was chosen for its ease of integration into the test facility. Also available from Steffes are large residential-size units, as well as commercial solutions. If space and water heating are both desired, hydronic units are available. All of the systems center on the use of the thermal bricks for energy storage, and have electric resistor elements to heat the bricks.

Figure 22. Steffes ETS Room Unit

2. Water

Using hot water as a storage medium allows for the use of simple water storage tanks with threaded plug-type diversion load resistance heaters. These types of are widely available in various voltage ratings and sizes. A model of a 190 liter (50 gallon) home water heater and two 1900 liter (500 gallon) storage tanks is presented in Figure 23. Coupling both large and small storage tanks allows for scaling of a hot water storage system.

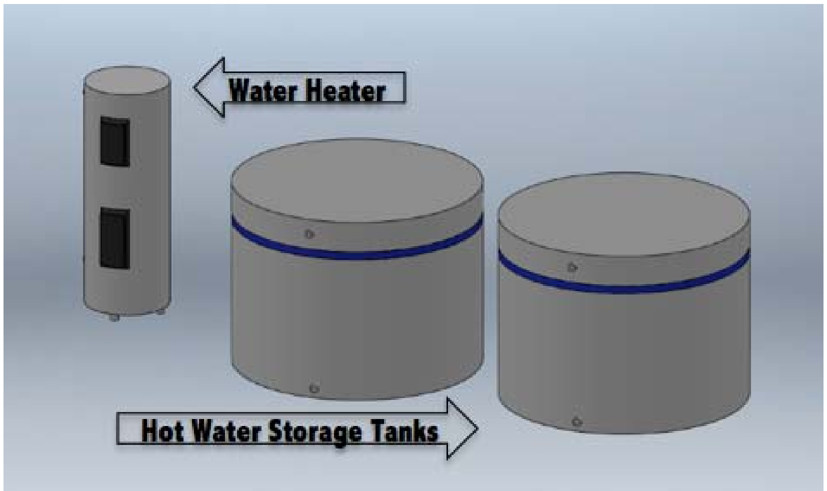

Figure 23. Model of a scalable hot thermal storage system using water

a. Scalability Challenge of Water-only Storage

In the case of thermal bricks with high temperature storage, water heating to high temperatures is easy to achieve. Using water as a thermal battery is more complex for the same kinds of high temperature demands. Tanks merely connected in series, and during periods where renewable generation is low, will result in a large quantity of lukewarm water and no water at the desired temperature. This necessitates a system where a small amount of water is kept hot enough for high temperature use and the remaining storage capacity is heated with energy above that required for the small tank. A control system is needed to solve this challenge.

b. System Control in Water-only Storage

Keeping in mind that a goal of this design is to store as much heat as possible, as fast as possible and to have a tank of hot water ready for use, the system control should result in a heat path like that shown in Figure 24.

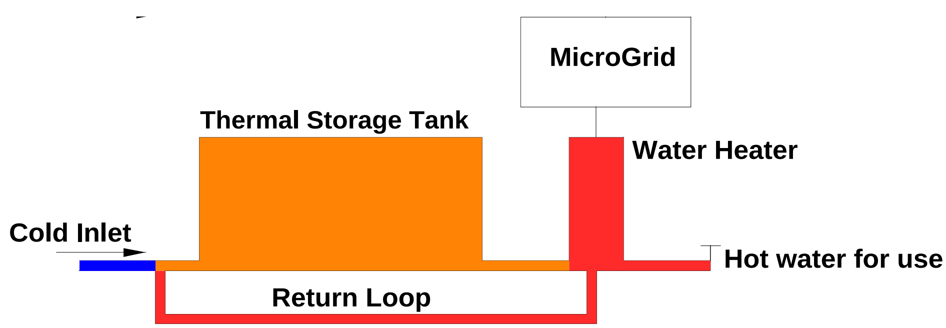

Figure 24. Heat path for system control in water-only storage.

The heater elements in the small tank should be set to the maximum temperature. This ensures all available power is applied to the heating elements. A water circulation pump should be attached to the tank with a controller that turns on the pump at a cut in temperature below the maximum temperature. Water will be pulled in from the storage tanks and the hot water will be fed back in a closed loop to be mixed into the storage tanks. The tanks now become the mixing zone for hot water returning from the small tank and cold water coming from the main supply. The circulation pump needs a controller to

increase the speed of the pump as the temperature of the small tank increases toward the maximum and stops the pump if the temperature drops below the cut in temperature. This ensures the small tank remains full and the heat is prioritized to it. The maximum speed of the pump should be linked to the maximum power input of the system heaters. In effect, the small tank should only be able to reach the maximum temperature when it and all the large tanks are all at the maximum temperature. This enables the maximum amount of energy to be stored in the system before the high temperature safety systems actuate. The system can be scaled up with the addition of storage tanks added in series with the first one resulting in a stepped heating of each successive tank.

3. Energy Density and Cost Justification

As stated in the Chapter I and shown in Figure 1 and Table 1, when compared to battery storage, thermal storage is arguably equal in energy density but superior in cost, safety, and life cycle. The basis for this comparison is specific to units investigated for integration into the NPS Turbopropulsion Lab facility. The estimates for water thermal storage were based on a 190 liter (50 gallon) hot water storage tank heated from 10^{o}C (50^{o}F) to 80^{o}C (180^{o}F), using a specific heat of water as 4.2 kJ/kg-K, and at an estimated cost of $300. The estimates for thermal bricks were based on the Steffes Corp. Electric Thermal Storage (ETS) Room Unit with a purchase price of $1500 and specifications from the product brochure available on the company website [31]. The water and brick systems have a comparable energy storage capacity of 15.5 kWh and 13.5 kWh, respectively, based on the amount of energy absorbed in heating to the maximum temperature. These are conservative estimates of cost per kilowatt hour, gravimetric energy density, and volumetric energy density.

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IV. FACILITY-SUITABLE DESIGN

A. NPS TURBOPROPULSION LAB

The last part of this study was to apply the designs, considerations, and various technologies presented in Chapter III to the NPS Turbopropulsion Lab facility. The first consideration was the larger project design goal and the current facility equipment and setup. This goal was a grid-tied microgrid capable of off-grid operation with controllable variable speed or variable energy equipment not dependent on battery storage for constant power. The already chosen plan architecture included two 4 kW UGE VisionAIR wind turbines, a grid tied, SMA America 18 kW 60 Hz 208V 3-Phase microgrid with a 41 kWh, 48 VDC Valve Regulated Lead Acid (VRLA) battery, and a 7.5 ton Trane Air-Cooled Liquid Chiller Model CGAM. The considerations for the microgrid were not dependent on the heating goals, and while the Davis [13] proved DC coupling of chilling units could be accomplished, an AC microgrid was chosen due to the size of a large commercial chilling units desired and their power requirement.

From this baseline there were four sources of heat energy originating from renewable sources explored. These heat sources are waste heat from the chilling plant, wind electric power from the wind turbines, (not yet implemented) solar electric energy, and (not yet implemented) solar thermal energy. Waste and solar thermal heating were rejected due to the higher complexity for an initial concept system.

As presented earlier in this study, many options existed for the thermal storage of heat. Paring down the list was based on criteria for the system:

- Realizable commercially in a short period of time
- Suitable in size for a test facility
- Reasonable in cost, and most importantly,
- Adaptable to the power following strategy.

The option chosen for initial integration, due to its simplicity, was the Steffes ETS Room Unit and a controller that fit into the power following strategy. This unit is only capable of room air heating.

B. A SCALABLE, FACILITY-SUITABLE DESIGN

To scale up the system design for a larger facility increases the complexity. A diversified system would be a combination of both the thermal brick and water storage mechanisms and all energy conversion and collection methods. The large commercial size Steffes hydronic systems with an integrated load controller programmed for a power following strategy provide the most secure and complete energy conversion and transfer mechanism and have a storage capacity of up to 480 kWh. Choosing the best size unit would be based on the maximum electric energy collection from wind and solar PV sources.

Increasing the stored capacity at a facility would most economically be achieved with water tanks. In addition to a significantly cheaper installation cost, water storage affords the option for integration of solar thermal and waste heat recovery since the hydronic units are electric only. The integration of solar thermal and waste heat allows for capitalization on the high generation, mid-day periods in a more efficient way than solar PV alone. Heat can be extracted from the hydronic units via hot water for storage in the water tanks, and increased storage can be achieved with additional tanks and a water pump and controller that follow the heat logics presented in scaling considerations from Chapter III. In this way, the facility achieves diversified methods of collection, reliable energy conversion, and inexpensive scalable storage. A model of what this type of system might look like at NPS is presented in Figure 25.

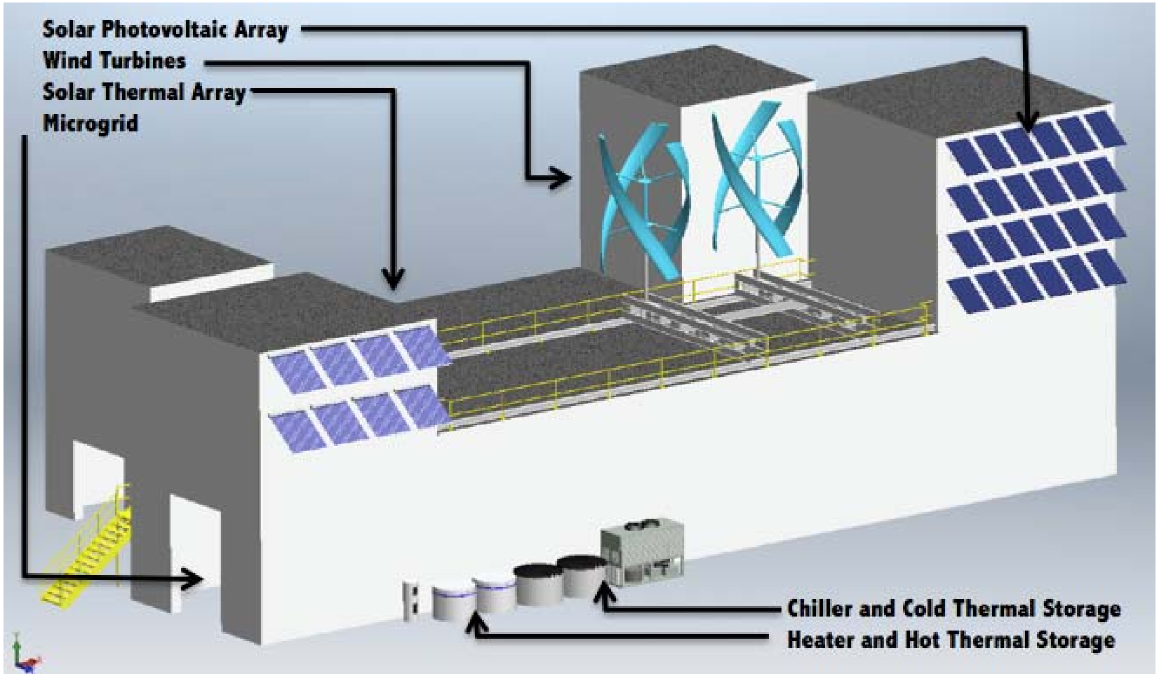

Figure 25. The NPS facility complete with diversified renewable collection and scalable thermal storage.

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V. DISCUSSION AND CONCLUSIONS

A. DISCUSSION

This thesis set out to present the design of and justification for a facility-scale renewable energy system based primarily on the thermal storage of heat. Chapter II demonstrated storage could overcome the intermittency challenge of renewable generation. The results of the parametric study showed a 70% reduction in the energy requirement was achieved even when demand for energy exceeded the average supply by only 25% in a small capacity system. In a similar manor, a large capacity system and a renewable supply profile that exceed demand achieved a 99.6% reduction. It is important to note that these results, while focused on thermal storage, are not limited to thermal storage. It is only when looked at in the context of cost that thermal storage clearly becomes the best option for storage. The results in Chapter I showed the thermal storage systems investigated very nearly equal to battery systems in energy density, but having a clear financial advantage in installation cost per kilowatt hour (kWh). Compared to lead acid batteries, thermal storage in bricks is 20% cheaper and in water is 76% cheaper. Compared to lithium-ion batteries, thermal storage in bricks is 72% cheaper and in water is 95% cheaper. Exacerbating this cost disparity between batteries and thermal storage, the graphical results in Chapter III showed that unless a significant overcapacity of storage is purchased, the storage system will be subjected to extreme cyclic loading throughout its life. Water and bricks sustain this type of extreme cyclic loading without degrading.

The addition of thermal storage to a facility with renewable power generation has the potential to cover a significant portion of the energy demand. Using the example of residential demand shown in Chapter I, a 15% reduction in electricity consumption could be achieved. Thermal storage also allows for the integration of diversified renewable generation. Unlike battery storage, thermal storage is not limited only to electricity-producing renewables. Solar thermal and waste heat solutions are facility scale-appropriate additions that can supplement solar PV and wind electric resources.

Integration of these technologies can be achieved in a scalable system with simple controls like the NPS facility in Chapter IV.

B. CONCLUSIONS

As high market penetration of PV becomes more common, cost savings will be achieved, but reliance on the standard practice of supplying the power produced to the commercial grid will not achieve increased energy security for DOD facilities. This is due to the reality that in most current systems when the grid fails, the renewable power systems must be turned off. Therefore, a goal of true energy security drives the solution toward facility microgrids capable of islanding. If the goal is both security and renewable-only installations, then storage must be achieved. Whether it is sunset or there is a lull in the wind, the two dominant sources of renewable energy—solar and wind—are intermittent with peak generation not always coinciding with peak demand. This makes large market penetration risky and prevents the technology from being used to its full capacity and potential. Battery storage is an ever-advancing technology, but storage on the scale required for a large facility is not economically practical. To achieve storage in a fiscally acceptable manner requires a storage method beyond batteries. Targeting the high-energy consumption requirements of space and water heating with the integration of thermal storage presents a way to significantly reduce the load on an electric power system. Thermal storage is significantly cheaper to install in large capacity, with water nearly an order of magnitude cheaper to install than the lead acid batteries. Installing renewable-only hot thermal storage systems has potential to reduced overall electricity demand on backup systems. Even the addition of a small capacity thermal storage has a significant effect. This multi-physics storage, coupled with the use of a renewable energy microgrid, would extend greatly the longevity of backup power systems and improve facility energy security, accomplishing the DOD objective at an acceptable cost.

VI. RECOMMENDATIONS

While this thesis presented the energy collection, conversion, and storage options and equipment for use in the multi-physics renewable facility, it did not detail power management and system control. Work will need to be done so the following control strategy for managing the power can be implemented. This includes a method for interrogating the incoming power and changing the speed and power requirements of the thermal loads.

In this design thesis, there was only thermal storage for thermal use. Future work should look at extracting electric energy from the thermal storage banks. With a temperature difference of over 700^{o}C (1300^{o}F) between the two hot and cold storage systems when fully charged, there exists an opportunity for a thermal-to-electric conversion. This might be in the form of solid-state thermoelectric modules or in the form of a Rankine cycle.

The cost benefits of thermal storage were limited to the specific equipment investigated. A thorough financial assessment of various systems and scalable storage should be investigated to determine the larger-scale benefit to the DOD.

All of the equipment implemented in the NPS Turbopropulsion Lab facility will have an efficiency based on the environmental conditions where it is installed. All performance efficiencies should be monitored and reported on so predictions can be made for its performance in a variety of conditions. Once efficiency and performance data is available, other potential work includes optimization of the microgrid for various load profiles.

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APPENDIX A

```
% Matlab script file to:
% read in wind data from Monterey Regional Airport
% determine power available based on a UGE 4kW vertical axis wind
turbine

clc; clear all; close all

FacilityScalingFactor=7*1.25;
MaxStorage=[13.5 50 100 150];

%% Wind Data File

% Data is read in from file
[NUM,~,~]=xlsread('MRY_hourly_observations_1998-2012.xlsx');

% Date Data is separated
Data.String = num2str(NUM(:,2));                    % Converts to
string
Data.Year   = str2num(Data.String(:,1:4));          % Strips out years
Data.Month  = str2num(Data.String(:,5:6));          % Strips out months
Data.Day    = str2num(Data.String(:,7:8));          % Strips out days
Data.Hour   = str2num(Data.String(:,9:10));         % Strips out hours
Data.Min    = str2num(Data.String(:,11:12));        % Strips out
minutes

% Windspeed Data is separated
Data.Wind    = NUM(:,4);                            % Wind Velocity in
mph
Data.Wind    = 1.6*Data.Wind/3.6;                   % Wind Velocity in
m/s
Data.WindCDF = sort(Data.Wind(~isnan(Data.Wind)));  % Not-a-Numbers
(nans excluded)

% To eliminate NaN
Data.Wind(isnan(Data.Wind)) = 0;

% Date is converted to Matlab date numbering system
Data.DateNumber = datenum(Data.Year,Data.Month,Data.Day,Data.Hour,...
    Data.Min,zeros(size(Data.Hour)));

% Windspeed is plotted against dates
figure(1); close; figure(1);
plot(Data.DateNumber,Data.Wind); grid on
datetick('x',10,'keepticks','keeplimits');
ylabel('Windvelocity [m/s]'); xlabel('Year')

% Cut in speed probability
% CDF data (p is stats examples)
```

```
Data.p          = linspace(0,1,size(Data.WindCDF,1));
[x(:,1),IA,IC] = unique(Data.WindCDF); % Keep only 1 data at each speed
y(:,1)         = (Data.p(IA))';
[x(:,2),IA,IC] = unique(Data.WindCDF,'first');% Keep only 1 data at
each speed
y(:,2)         = (Data.p(IA))';

% average of the two
x = mean(x,2);
y = mean(y,2);

%Turbine cut in speed
Data.CutInSpeed = 4;                              %[m/s]

Data.CutInSpeedCDF = interp1(x,y,Data.CutInSpeed); % Probability
Data.CutInSpeedCDF;

% Plot integral of windspeed distribution
figure(2); close; figure(2);
plot(Data.WindCDF,Data.p,'+-b'); hold on
plot(x,y,'-or')
plot(Data.CutInSpeed,Data.CutInSpeedCDF,'ok')
plot([Data.CutInSpeed Data.CutInSpeed],[0 Data.CutInSpeedCDF],'-ok')
plot([0 Data.CutInSpeed],[Data.CutInSpeedCDF Data.CutInSpeedCDF],'-ok')
ylabel('Cumalitive Distribution Function'); xlabel('Wind velocity
[m/s]')

% Memory cleanup
clear Data.String NUM

%% Turbine Data File
% Data is read in from file
[NUM,~,~]=xlsread('Turbine_Specifications.xlsx');

% Wind velocity and turbine power data is separated
WindTurb.WindVel=NUM(:,1);
WindTurb.Power=NUM(:,2);

% Wind data interpolated onto turbine power curve
Data.PowerRaw=interp1(WindTurb.WindVel,WindTurb.Power,Data.Wind);

% Plot of turbine power vs. time
figure(3);close;figure(3);
plot(Data.DateNumber,Data.PowerRaw);grid on;
datetick('x',10,'keepticks','keeplimits');
ylabel('Power [kW]'); xlabel('Year')

% Raw energy accumulated
Data.EnergyRaw=cumtrapz(Data.DateNumber*24,Data.PowerRaw);

% Plot of raw energy accumulated vs. time
figure(4);close;figure(4);
```

```
plot(Data.DateNumber,Data.EnergyRaw);grid on;
ylabel('Energy [kWh]'); xlabel('Year');
datetick('x');

%% 10 Year Storage Analysis

% Daily sample power demand
FractionOfDailyDemand=[.011 .011 .015 .015 .015 .015 .015 .014...
    .014 .014 .016 .022 .026 .026 .027 .027 .027 .024 .024 .023...
    .020 .020 .020 .020 .019 .018 .018 .018 .018 .018 .019 .019...
    .021 .021 .019 .019 .03 .03 .03 .03 .029 .029 .029 .027 .025...
    .023 .01 .01 .01]';
Demand=FractionOfDailyDemand*FacilityScalingFactor;

% Plot of daily sample power demand
NominalDay=(0:.5:24)';
figure(5);close;figure(5);
plot(NominalDay,FractionOfDailyDemand);grid on;
ylabel('Fraction of Power Demand'); xlabel('Hour')
axis([0 24 0 .04])

% Daily demand accumulated
NominalDayAccum=-cumtrapz(NominalDay*2,FractionOfDailyDemand);

% Plot of daily sample demand accumulated vs. time
figure(6);close;figure(6);
plot(NominalDay,NominalDayAccum);grid on;
ylabel('Total Energy'); xlabel('Hour')
axis([0 24 -1 0])

% Daily sample power demand repeated for total time
Data.DemandDates=(datenum(2000,1,1,0,0,0):1/48:datenum(2011,1,1,0,0,0))
';
Data.DemandRates=zeros(size(Data.DemandDates));
for ii=Data.DemandDates(1):(Data.DemandDates(end)-1)
    Data.DemandRates(Data.DemandDates>=ii &...
        Data.DemandDates<=(ii+1))=Demand;
end % for ii

% Turbine power interpolated onto demand data time steps
Data.PowerMapped=interp1(Data.DateNumber,Data.PowerRaw,Data.DemandDates
);

% Plot of turbine power and interpolated power vs. time
figure(7);close;figure(7);
plot(Data.DemandDates,Data.PowerMapped); grid on;
datetick('x');
ylabel('Power [kW]'); xlabel('Year')
axis([datenum(2000,1,1,0,0,0) datenum(2011,1,1,0,0,0) 0 4.5])

% Total energy accumulated
Data.EnergyTotal=cumtrapz(Data.DemandDates*24,Data.PowerMapped);
```

```
%% Plot of total energy accumulated vs. time
figure(8);close;figure(8);
plot(Data.DemandDates,Data.EnergyTotal);grid on;
ylabel('Energy [kWh]'); xlabel('Year');
datetick('x');
axis('tight')

%% Total demand accumulated
Data.DemandTotal=-cumtrapz(Data.DemandDates*24,Data.DemandRates);

% Plot of total demand accumulated vs. time
figure(9);close;figure(9);
plot(Data.DemandDates,Data.DemandTotal);grid on;
ylabel('Energy [kWh]'); xlabel('Year');
datetick('x');
axis('tight')

%% Storage,power purchased, & power sold for various storage sizes

for kk=1:length(MaxStorage)
    Data.Storage=zeros(size(Data.DemandDates));
    Data.Sold=zeros(size(Data.DemandDates));
    Data.Purchased=zeros(size(Data.DemandDates));

    for jj=2:(size(Data.DemandDates))
        Data.Storage(jj)=Data.Storage(jj-1)+Data.PowerMapped(jj)-...
            Data.DemandRates(jj);
        if Data.Storage(jj)>=MaxStorage(kk)
            Data.Storage(jj)=MaxStorage(kk);
            Data.Sold(jj)=Data.PowerMapped(jj)-Data.DemandRates(jj);
        elseif Data.Storage(jj)<0
            Data.Storage(jj)=0;
            Data.Purchased(jj)=Data.PowerMapped(jj)-
Data.DemandRates(jj);
        else
            Data.Storage(jj);
        end
    end

    % Plot of storage vs. time
    figure(9+kk);close;figure(9+kk);
    plot(Data.DemandDates,Data.Storage)
    hold on
    plot(Data.DemandDates,Data.Purchased, 'r')
    plot(Data.DemandDates,Data.Sold, 'g')
    ylabel('Storage [kWh]  &  Power  [kW]'); xlabel('Year');
    datetick('x', 'keeplimits');

    % Analysis & display
    Data.SoldTotal=cumtrapz(Data.DemandDates*24,Data.Sold);
    Data.PurchasedTotal=cumtrapz(Data.DemandDates*24,Data.Purchased);
    StorageEmpty=size(find(Data.Storage==0))/size(Data.Storage)*100;
```

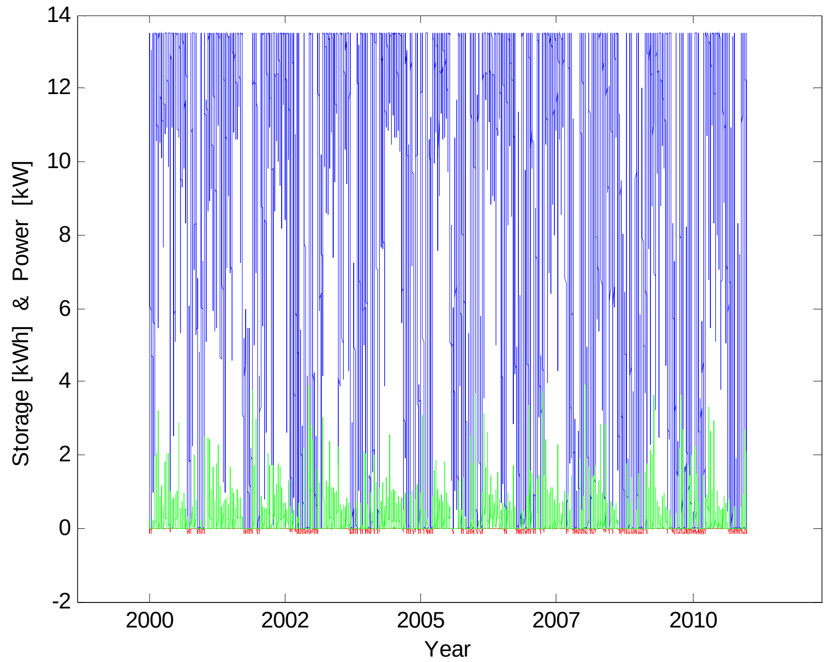
```
    StorageFull=size(find(Data.Storage==MaxStorage(kk)))/...
        size(Data.Storage)*100;

    disp('Totals Over a 10 Year Period')
    disp('  ')
    fprintf('Demand       %-2.1f kWH \n', sum(Demand))
    fprintf('Storage Size %-2.1f kWH \n', MaxStorage(kk))
    fprintf('Produced     %-5.1f  MWH \n', Data.EnergyTotal(end)/1000)
    fprintf('Used         %-5.1f  MWH \n', -Data.DemandTotal(end)/1000)
    fprintf('Purchased    %-5.1f kWH \n', -Data.PurchasedTotal(end))
    fprintf('Sold         %5.1f kWH \n',Data.SoldTotal(end))
    fprintf('P Full       %3.1f \n', StorageFull)
    fprintf('P Empty      %3.1f \n', StorageEmpty)
    fprintf('P Sold       %3.1f \n', Data.SoldTotal(end)/...
        Data.EnergyTotal(end)*100)
    fprintf('P Purch      %3.1f \n', Data.PurchasedTotal(end)/...
        Data.DemandTotal(end)*100)
end

%% Zoomed 1 Week Analysis

% Plot of interpolated power vs. 1 week of time
figure(14);close;figure(14);
plot(Data.DemandDates,Data.PowerMapped)
ylabel('Power [kW]'); xlabel('Day')
axis([datenum(2000,1,1,0,0,0) datenum(2000,1,8,0,0,0) 0 .8])
set(gca,'XTickLabel',{'0'; '1'; '2'; '3'; '4'; '5'; '6'; '7'; '8'})

% Plot of repeated daily demand vs. 1 week of time
figure(15);close;figure(15);
plot(Data.DemandDates,Data.DemandRates)
ylabel('Power [kW]'); xlabel('Day')
axis([datenum(2000,1,1,0,0,0) datenum(2000,1,8,0,0,0) 0 .3])
set(gca,'XTickLabel',{'0'; '1'; '2'; '3'; '4'; '5'; '6'; '7'; '8'})

% Plot of total energy accumulated vs. 1 week of time
figure(16);close;figure(16);
plot(Data.DemandDates,Data.EnergyTotal);grid on;
ylabel('Energy [kWh]'); xlabel('Day');
axis([datenum(2000,1,1,0,0,0) datenum(2000,1,8,0,0,0) 0 25])
set(gca,'XTickLabel',{'0'; '1'; '2'; '3'; '4'; '5'; '6'; '7'; '8'})

% Plot of total demand accumulated vs. 1 week of time
figure(17);close;figure(17);
plot(Data.DemandDates,Data.DemandTotal);grid on;
ylabel('Energy [kWh]'); xlabel('Day');
axis([datenum(2000,1,1,0,0,0) datenum(2000,1,8,0,0,0) -25 0])
set(gca,'XTickLabel',{'0'; '1'; '2'; '3'; '4'; '5'; '6'; '7'; '8'})

% Plot of energy storage vs. 1 week of time
% Annotations marked for a plot of demand with a scaling factor=7.

MaxStorageWk=2;
```

```
Data.StorageWk=zeros(size(Data.DemandDates));
Data.SoldWk=zeros(size(Data.DemandDates));
Data.PurchasedWk=zeros(size(Data.DemandDates));

for jj=2:(size(Data.DemandDates))
    Data.StorageWk(jj)=Data.StorageWk(jj-1)+Data.PowerMapped(jj)-...
        Data.DemandRates(jj);
    if Data.StorageWk(jj)>=MaxStorageWk
        Data.StorageWk(jj)=MaxStorageWk;
        Data.SoldWk(jj)=Data.PowerMapped(jj)-Data.DemandRates(jj);
    elseif Data.StorageWk(jj)<0
        Data.StorageWk(jj)=0;
        Data.PurchasedWk(jj)=Data.PowerMapped(jj)-Data.DemandRates(jj);
    else
        Data.StorageWk(jj);
    end
end

% Plot of storage vs. time
figure(18);close;figure(18);
plot(Data.DemandDates,Data.StorageWk)
hold on
plot(Data.DemandDates,Data.PurchasedWk, 'r')
plot(Data.DemandDates,Data.SoldWk, 'g')
ylabel('Storage [kWh]  &  Power [kW]'); xlabel('Day');
axis([datenum(2000,1,1,0,0,0) datenum(2000,1,8,0,0,0) -.5 2.5])
set(gca,'XTickLabel',{'0'; '1'; '2'; '3'; '4'; '5'; '6'; '7'; '8'})
annotation('textarrow',[0.432142857142857 0.375],...
    [0.830952380952381 0.790476190476191],'TextEdgeColor','none',...
    'String',{'Max Storage'});
annotation('textarrow',[0.439285714285714 0.346428571428571],...
    [0.610904761904762 0.480952380952381],'TextEdgeColor','none',...
    'String',{'Storage Charge'});
annotation('textarrow',[0.4375 0.385714285714286],...
    [0.70952380952381 0.652380952380952],'TextEdgeColor','none',...
    'String',{'Storage Discharge'});
annotation('textarrow',[0.439285714285714 0.371428571428571],...
    [0.469047619047619 0.330952380952381],'TextEdgeColor','none',...
    'String',{'Power Sold'});
annotation('textarrow',[0.496428571428571 0.546428571428571],...
    [0.171428571428571 0.204761904761905],'TextEdgeColor','none',...
    'String',{'Power Puchased'});
```

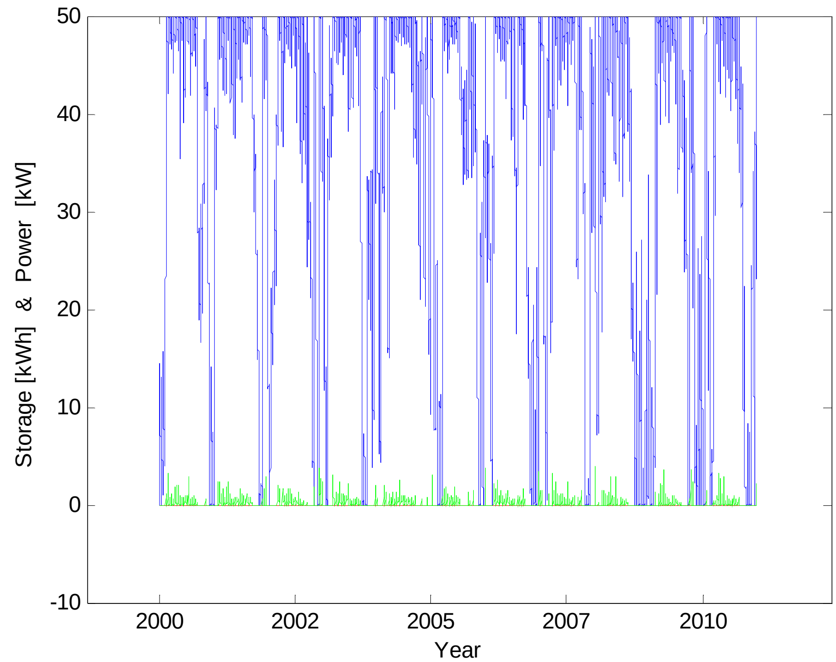
APPENDIX B

Results of the parametric study are provided as Appendix B.

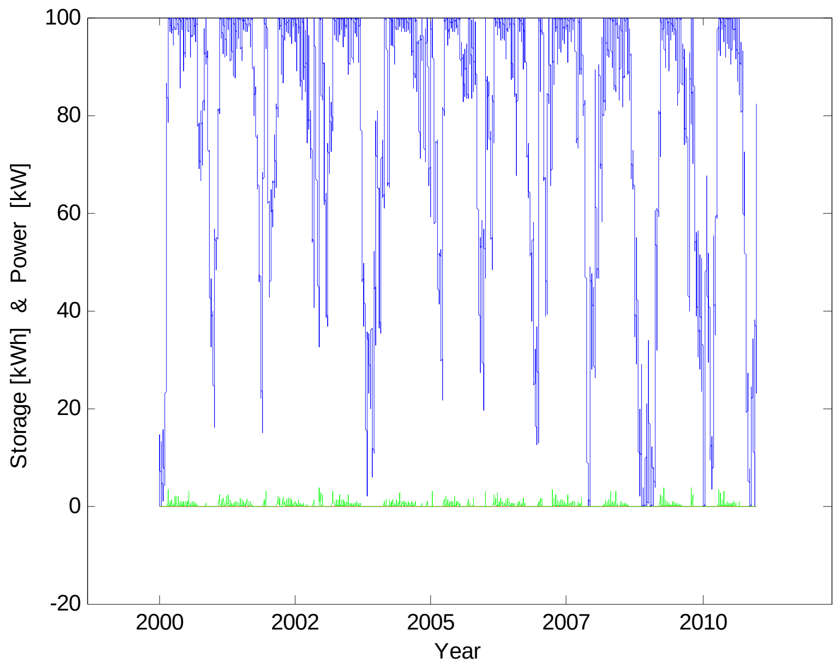
The results are in the order of; demand = 5.3 kWH : 75% of supply, demand = 7.0 kWH : 100% of supply, and demand = 8.7 kWh : 125% of supply. The storage sizes are in the order of 13.5 kWh, 50 kWh, 100 kWh, and 150 kWh.



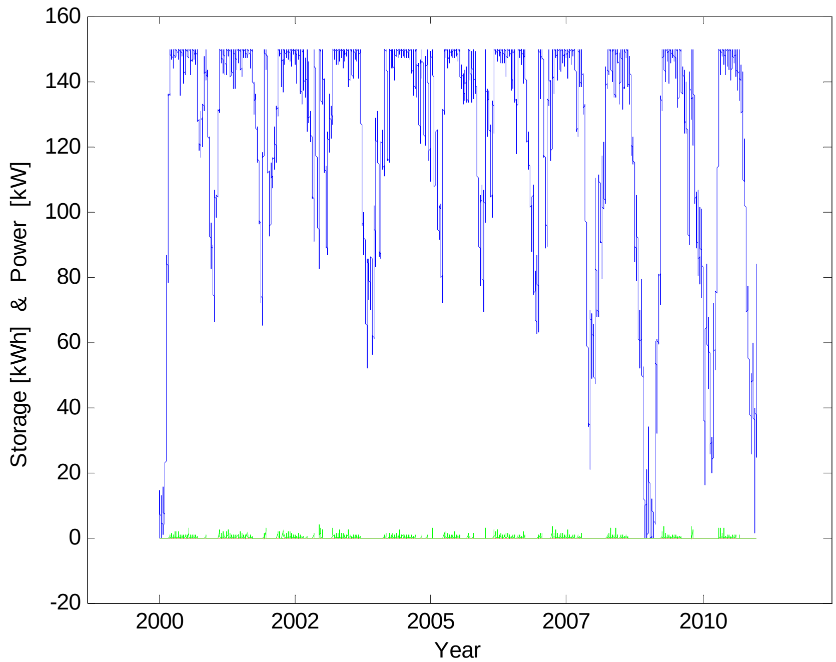
Plot of storage level with a capacity of 13.5 kWh.



Plot of storage level with a capacity of 50 kWh.



Plot of storage level with a capacity of 100 kWh.



Plot of storage level with a capacity of 150 kWh.

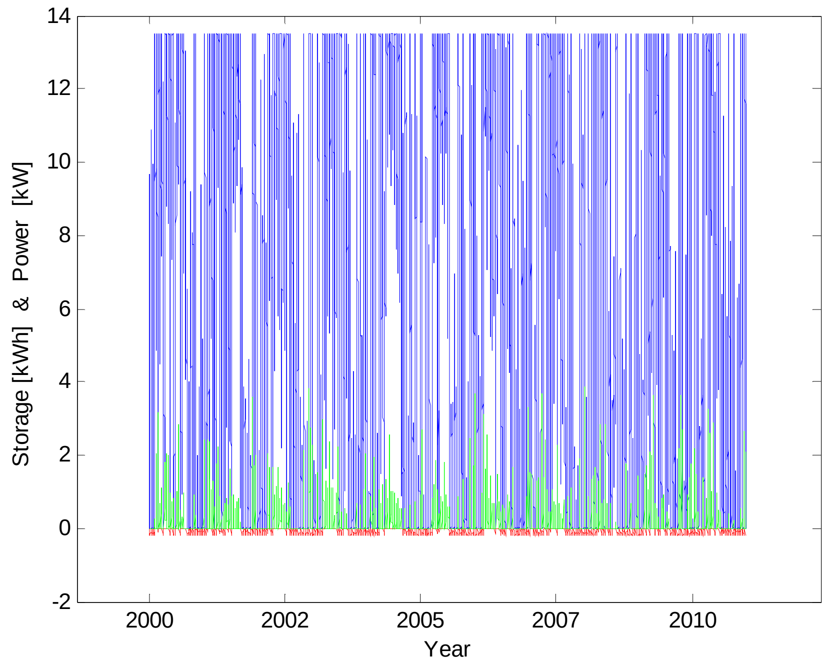
Totals over a 10-year period with demand = 5.3 kWH : 75% of supply.

Storage Size	13.5 kWH
Produced	13.9 MWH
Used	10.4 MWH
Purchased	993.1 kWH
Sold	4580.5 kWH
% Full	14.8
% Empty	11.2
% Sold	32.9
% Purchased	9.5

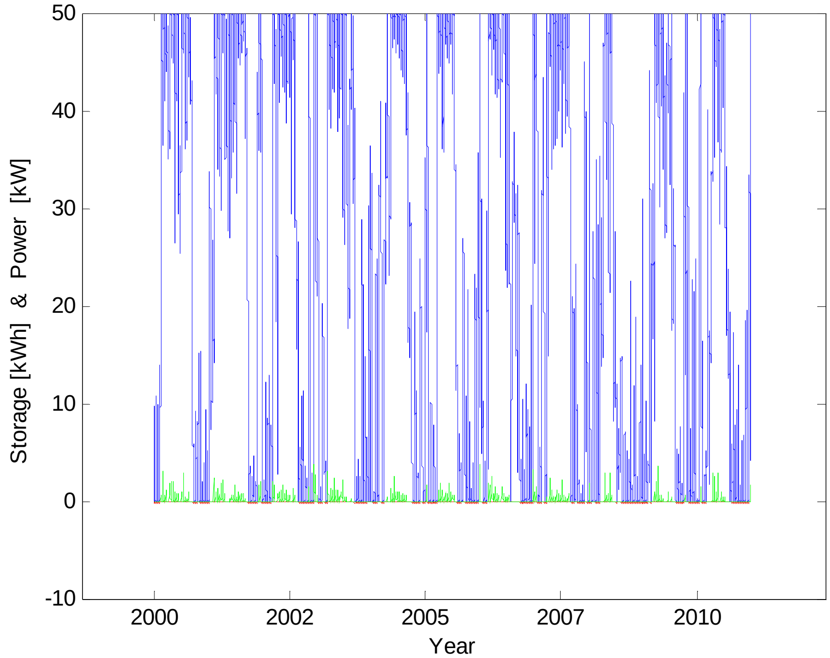
Storage Size	50.0 kWH
Produced	13.9 MWH
Used	10.4 MWH
Purchased	379.8 kWH
Sold	3943.4 kWH
% Full	13.1
% Empty	4.2
% Sold	28.4
% Purchased	3.6

Storage Size	100.0 kWH
Produced	13.9 MWH
Used	10.4 MWH
Purchased	123.4 kWH
Sold	3669.1 kWH
% Full	12.5
% Empty	1.3
% Sold	26.4
% Purchased	1.2

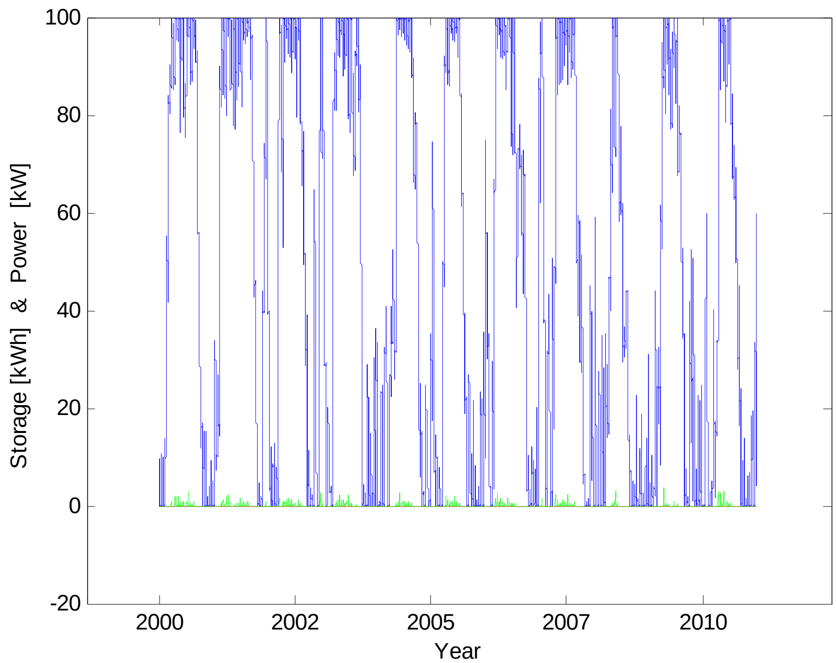
Storage Size	150.0 kWH
Produced	13.9 MWH
Used	10.4 MWH
Purchased	41.3 kWH
Sold	3584.3 kWH
% Full	12.3
% Empty	0.5
% Sold	25.8
% Purchased	0.4



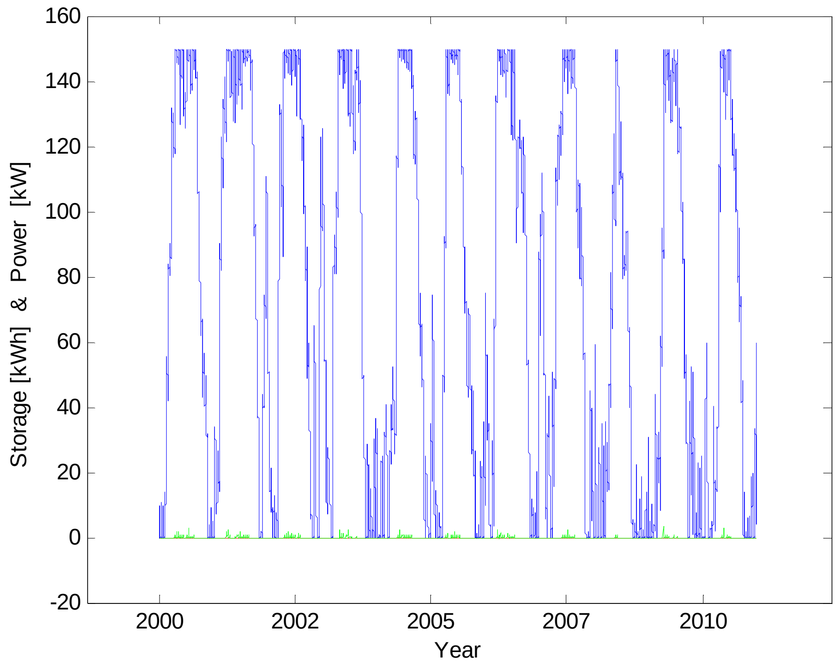
Plot of storage level with a capacity of 13.5 kWh.



Plot of storage level with a capacity of 50 kWh.



Plot of storage level with a capacity of 100 kWh.



Plot of storage level with a capacity of 150 kWh.

Totals over a 10-year period with demand = 7.0 kWH : 100% of supply

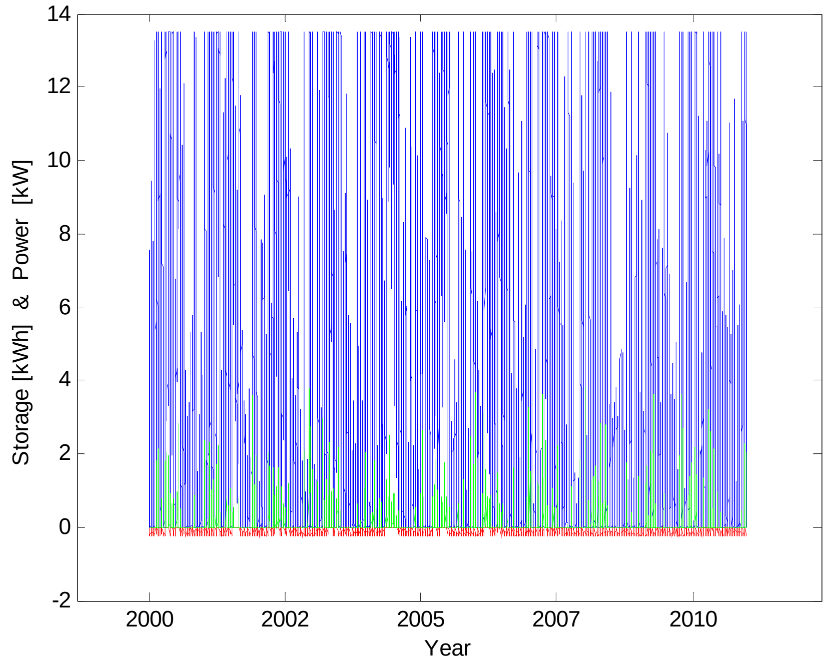
Storage Size	13.5 kWH
Produced	13.9 MWH
Used	13.9 MWH
Purchased	2786.4 kWH
Sold	2805.3 kWH
% Full	8.0
% Empty	23.6
% Sold	20.2
% Purchased	20.0

Storage Size	50.0 kWH
Produced	13.9 MWH
Used	13.9 MWH
Purchased	1965.6 kWH
Sold	1960.1 kWH
% Full	6.1
% Empty	16.6
% Sold	14.1
% Purchased	14.1

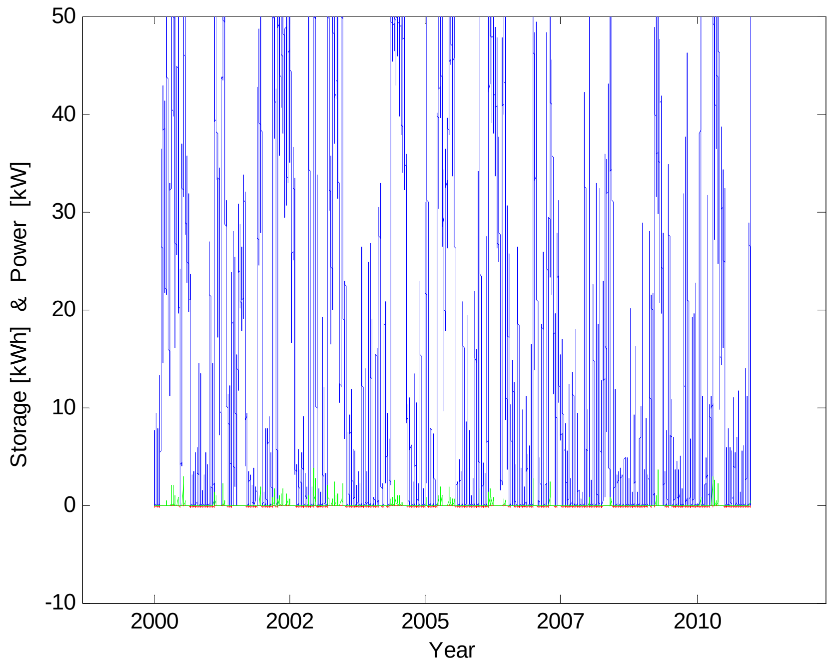
Storage Size 100.0 kWH

Produced	13.9 MWH
Used	13.9 MWH
Purchased	1563.1 kWH
Sold	1547.9 kWH
% Full	5.2
% Empty	13.2
% Sold	11.1
% Purchased	11.2

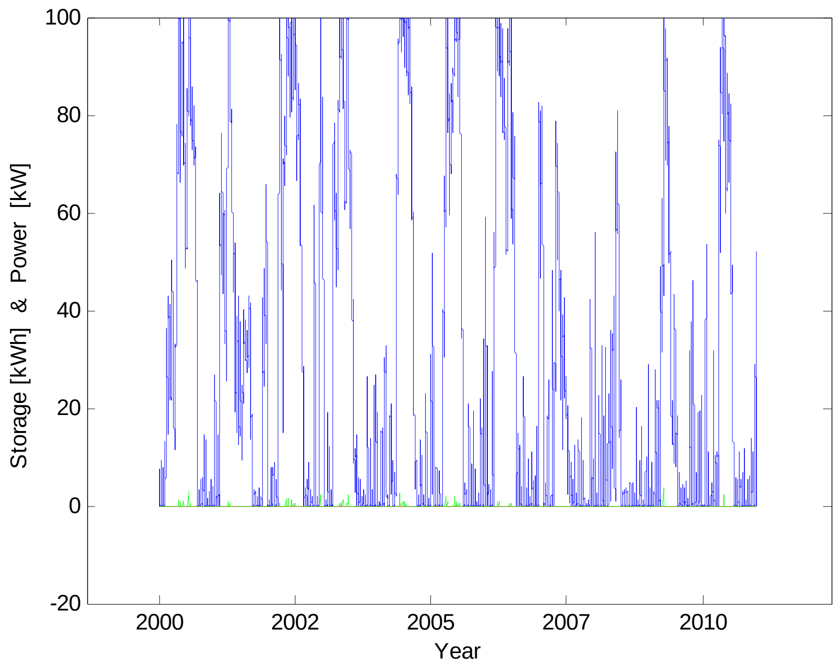
Storage Size	150.0 kWH
Produced	13.9 MWH
Used	13.9 MWH
Purchased	1256.5 kWH
Sold	1236.7 kWH
% Full	4.3
% Empty	10.6
% Sold	8.9
% Purchased	9.0



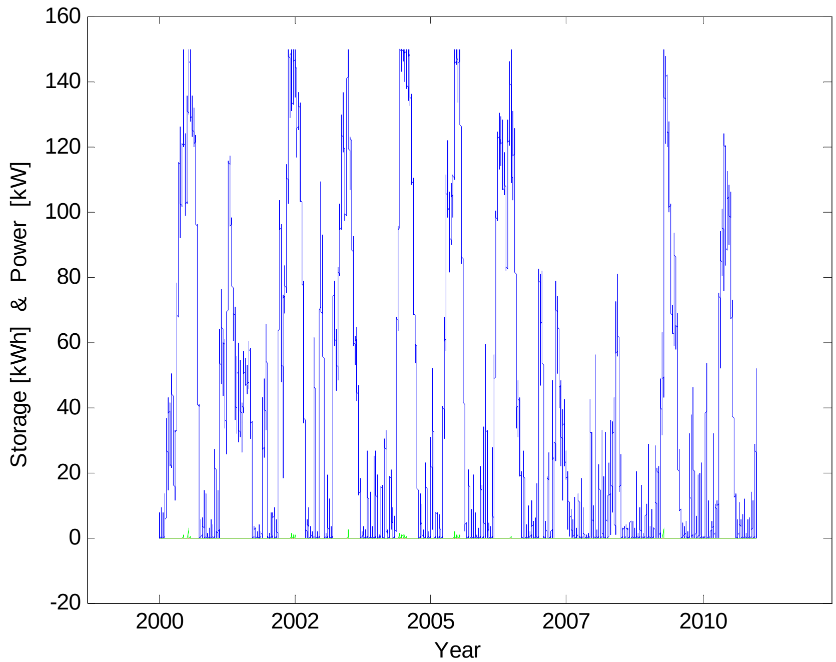
Plot of storage level with a capacity of 13.5 kWh.



Plot of storage level with a capacity of 50 kWh.



Plot of storage level with a capacity of 100 kWh.



Plot of storage level with a capacity of 150 kWh.

Totals over a 10-year period with demand = 8.7 kWh : 125% of supply

Storage Size	13.5 kWH
Produced	13.9 MWH
Used	17.4 MWH
Purchased	5256.1 kWH
Sold	1713.3 kWH
% Full	4.0
% Empty	35.7
% Sold	12.3
% Purchased	30.2

Storage Size	50.0 kWH
Produced	13.9 MWH
Used	17.4 MWH
Purchased	4319.2 kWH
Sold	744.4 kWH
% Full	1.9
% Empty	29.2
% Sold	5.4
% Purchased	24.8

Storage Size 100.0 kWH

Produced	13.9	MWH
Used	17.4	MWH
Purchased	3972.0	kWH
Sold	391.9	kWH
% Full	1.2	
% Empty	26.9	
% Sold	2.8	
% Purchased	22.8	

Storage Size	150.0	kWH
Produced	13.9	MWH
Used	17.4	MWH
Purchased	3766.5	kWH
Sold	183.7	kWH
% Full	0.6	
% Empty	25.5	
% Sold	1.3	
% Purchased	21.6	

LIST OF REFERENCES

[1] B.H. Newell, “The evaluation of HOMER as a Marine Corps expeditionary energy pre-deployment tool,” M.S. thesis, Dept Elec. Eng., Naval Postgraduate School, Monterey, CA, 2013.

[2] Department of Defense, “DOD energy policy,” *DOD DIR 4180.01* Washington, DC: DOD, 2011.

[3] Department of Defense, “Installation energy management,” *DOD INST 4170.11*, Washington, DC: DOD, 2009.

[4] “SPIDERS,” Sandia National Laboratories [Online] Available: http://energy.sandia.gov/?page_id=2781. Accessed 5 May 2014.

[5] C. Casey. (2013, 02, 12). “In first test, US Military’s SPIDERS microgrid uses 90% renewable energy,” Cleanteachnica.com [Online] Available: http://cleantechnica.com/2013/02/12/u-s-militarys-new-spiders-renewable-energy-microgrid/

[6] “Electricity explained, use of electricity,” US Energy Information Administration, [Online] Available: http://www.eia.gov/energyexplained/index.cfm?page=electricity_use. Accessed 2 May 2014.

[7] “Batteries for oxygen concentrators,” NASA Glen Research Center [Online]. Available: https://electrochemistry.grc.nasa.gov/current-projects/batteries-for-o2-concentrators/. Accessed: 25 May 2014.

[8] “Electrochemical energy,” Electropedia. [Online]. Available: http://www.mpoweruk.com/chemical_energy.htm. Accessed: 23 May 2014.

[9] S.B. Van Broekhoven, N. Judson, S.V.T. Nguyen, and W.D. Ross, “Microgrid study: energy security for DOD installations,” Lincoln Laboratory, MIT, Lexington MA Tech. Rep. 1164, 2012.

[10] T. Ersal, C. Ahn, I.A. Huskens, H. Peng, and J.L. Stein, “Impact of controlled plug-in EVs on microgrids: a military microgrid example.” in Power and Energy Society General Meeting, San Diego, CA, 2011. IEEE doi: 10.1109/PES.2011.6039620.

[11] A.F. Skoronska-Kurec, S.T. Eick, and E.T. Kallio. “Demonstration of microgrid technology at a military installation,” in Power and Energy Society General Meeting, San Diego, CA, 2012. IEEE doi: 10.1109/PESGM.2012.6344923.

[12] L.M. Olson, “Initial investigation of a novel thermal storage concept as a part of a renewable energy system,” M.S. thesis, Mech. Eng., Naval Postgraduate School, Monterey, CA, 2013.

[13] H.C. Davis, “Wind-electric ice making for developing world villages,” M.S. thesis, Dept. Civil Eng, University of Colorado, Boulder, CO, 1994.

[14] M.J. Kazmierczak, S. Krishnamoorthy, and A. Gupta, “Experimental testing of a thermoelectric-based hydronic cooling and heating device with transient charging of sensible thermal energy storage water tank,” J. Thermal Sci. Eng. Appl. 1, 041005, 2010. doi:10.1115/1.4001456.

[15] Paul Steffes, P.E., “Grid-interactive electric thermal storage (GETS) water heating,” Steffes Corp, Dickson, ND, White Paper SC12012 Rev 4, [Online] Available from: http://www.steffes.com/literatureretrieve.aspx?id=115580.

[16] Paul Steffes, P.E., “Advanced thermal energy storage for direct load control in a low load growth, high DG future,” Steffes Corp. Dickson, ND, Unpublished.

[17] R. Pokhrel, J. E. González, T. Hight, and T. Adalsteinsson, “Analysis and design of a paraffin/graphite composite PCM integrated in a thermal storage unit,” J. Sol. Energy Eng. 132, 041006, 2010. doi:10.1115/1.4001473.

[18] Z. Ma, G. C. Glatzmaier, and C. F. Kutscher, “Thermal energy storage and its potential applications in solar thermal power plants and electricity storage,” Proc. of ASME 2011 5th International Conference on Energy Sustainability & 9th Fuel Cell Science, Engineering and Technology Conference, 2011. doi:10.1115/ES2011-54077.

[19] H. Wei, W. Xin, G. Jianhuan, Z. Jianhua, and Y Jingyan, “Discussion on application of super capacitor energy storage system in microgrid,” in International Conference on Sustainable Power Generation and Supply, Janjing, China, 2009. IEEE; doi: 10.1109/SUPERGEN.2009.5348079.

[20] Y. Lee, Y. Chang, C. Chan. Y. Ho. “Preliminary implementation of microgrid with photovoltaic and microturbine for stand alone operation,” in Industry Applications Society Annual Meeting (IAS), Las Vegas, NV, 2012. IEEE; doi: 10.1109/IAS.2012.6373988.

[21] W. Yang, A. Xin, and G. Yang. “Microgrid’s operation-management containing distributed generation system,” in IEEE 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), Weihai, Shandong, China, 2011. doi: 10.1109/DRPT.2011.5993983.

[22] P.E. Phelan, R. Calhoun, S. Trimble, J.E. Baker, and J. Sherbeck, "Heat-pump-based thermal storage for intermittent electrical and thermal sources," ASME/JSME 2011 8th Thermal Engineering Joint Conference, 2011. doi:10.1115/AJTEC2011-44163.

[23] M. L. Ferrari, M. Pascenti, A. Traverso, and M. Rivarolo, "Smart polygeneration grid: a new experimental facility," *Proc. of ASME Turbo Expo 2012*, GT2012-68585, 2012.

[24] "Dynamic maps, GIS data, & analysis tools," NREL.gov [Online]. Available: http://www.nrel.gov/gis/solar.html. Accessed: 7 May 2014.

[25] "Dynamic maps, GIS data, & analysis tools," NREL.gov [Online]. Available: http://www.nrel.gov/gis/wind.html. Accessed: 7 May 2014.

[26] "Building technologies office," Office of Energy Efficiency & Renewable Energy [Online]. Availbable: http://energy.gov/eere/buildings/building-technologies-office. Accessed: 5 June 2014.

[27] Y. Chiou, "Deriving U.S. household energy consumption profiles from American time use survey data – a bootstrap approach," in Eleventh International IBSPA Conference, Glasgow, Scotland, 2009.

[28] NAHB Reasearch Center, "Review of residential electrical energy use data," Upper Marlboro, MD: NAHB Reasearch Center, 2001.

[29] "National Renewable Energy Laboratory," NREL.gov [Online]. Available: http://www.nrel.gov/. Accessed: 5 May 2014.

[30] "Electric thermal storage," South Kentuckey Rural Electric Cooperative Corporation [Online]. Available: http://www.skrecc.com/ets.htm. Accessed 20 May 2014.

[31] "Off peak heating for the homeowner," Steffes Corporation, [Online]. Available: http://www.steffes.com/off-peak-heating/ets.html. Accessed: 29 January 2014.

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